SYLLABUS

Protection and Switchgear - (EE3601)

UNIT I PROTECTION SCHEMES

Significance and need for protective schemes - nature and causes of faults - types of faults Effects of faults - Zones of protection and essential qualities of protection - Types of Protection schemes - Power system Grounding and Methods of Grounding. **(Chapter - 1)**

UNIT II BASICS OF RELAYS

Operating principles of relays - Universal torque equation - R-X diagram - Electromagnetic Relays - Over current, Directional and non-directional, Distance, Differential, Negative sequence and Under frequency relays. **(Chapter - 2)**

UNIT III OVERVIEW OF EQUIPMENT PROTECTION

Current transformers and Potential transformers and their applications in protection schemes - Protection of transformer, generator, motor, bus bars and transmission line. **(Chapters - 3, 4, 5)**

UNIT IV STATIC RELAYS AND NUMERICAL PROTECTION

Static relays - Phase, Amplitude Comparators - Synthesis of various relays using Static comparators - Block diagram of Numerical relays - Over current protection, transformer differential protection, and distantce protection of transmission lines. **(Chapter - 6)**

UNIT V CIRCUIT BREAKERS

Physics of arcing phenomenon and arc interruption - DC and AC circuit breaking - re-striking voltage and recovery voltage - rate of rise of recovery voltage - current chopping - interruption of capacitive current - resistance switching - Types of circuit breakers - air blast, oil, SF_6 and vacuum circuit breakers - comparison of different circuit breakers - HVDC Breaker. **(Chapters - 7, 8)**

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UNIT I

1

Protection Schemes

Syllabus

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. . . . · Marks 12
1.12 Introduction to Insulation Co-ordination . . . . . **May-13,15, Dec.-13,14** · · · · Marks 8
1.13 Two Marks Questions with Answers
1.14 University Questions with Answers (Long Answered Questions)

1.1 Introduction

Protective relaying is one of the several features of the power system design. Every part of the power system is protected. The factors affecting the choice of protection are type and rating of equipment, location of the equipment, types of faults, abnormal conditions and cost.

The protective relaying is used to give an alarm or to cause prompt removal of any element of power system from service when that element behaves abnormally. The abnormal behaviour of an element might cause damage or interference within effective operation of rest of the system. The protective relaying minimises the damage to the equipment and interruptions to the service when electrical failure occurs. Along with some other equipments the relays help to minimise damage and improve the service.

The relays are compact and self contained devices which can sense the abnormal conditions. Whenever an abnormal condition exists, the relay contacts get closed. This inturn closes the trip circuit of a circuit breaker. The circuit breakers are capable of disconnecting a faulty element, when they are called upon to do so by the relays. Thus entire process includes the operations like occurrence of fault, operation of relay, opening of a circuit breaker and removal of faulty element. This entire process is automatic and fast, which is possible due to effective protective relaying scheme.

The protective relaying scheme includes protective current transformers, voltage transformers, protective relays, time delay relays, auxiliary relays, secondary circuits, trip circuits etc. Each component plays its own role, which is very important in the overall operation of the scheme. The protective relaying is the team work of all these components. The protective relaying also provides the indication of location and type of the fault.

1.2 Need for Protective Schemes

AU : Dec.-04, May-14

The protective relaying is necessary in the power system to perform following functions :

1. The prompt removal of the component which is behaving abnormally by closing the trip circuit of circuit breaker or to sound an alarm.
2. To disconnect the abnormally operating part so as to avoid the damage or interference within effective operation of the rest of system.
3. To prevent the subsequent faults by disconnecting the abnormally operating part.
4. To disconnect the faulty part as quickly as possible so as to minimise the damage to the faulty part itself. For example, if there is a winding fault in a machine and if it persists for a long time then there is a possibility of the damage of the entire

winding. As against this, if it is disconnected quickly then only few coils may get damaged instead of the entire winding.

5. To restrict the spreading of the effect of fault causing least interference to the rest of the healthy system. Thus by disconnecting the faulty part, the fault effects get localised.
6. To improve the system performance, system reliability, system stability and service continuity.

The faults can not be completely avoided but can be minimised. Thus the protective relaying plays an important role in sensing the faults, minimizing the effects of faults and minimizing the damage due to the faults.

Review Question

1. *State the various functions of protective relaying.* **AU : May-14, Dec.-04, Marks 6**

1.3 Introduction to Fault in a Power System

An operating mode of a power system, in steady state is a balanced three phase a.c. A fault is said to occur on a power system when the defect in electrical circuit of a power system deviates the current path from its intended path. When a fault occurs on a system, the voltages of the three phases become unbalanced. The fault currents are very large in magnitude which may damage the apparatus. The flow of power which is diverted towards the fault affects the supply to the neighbouring zone. Hence the analysis of such faults is an essential step in a power system analysis. The fault analysis means to find the voltage and current distribution throughout the system during the occurance of a fault. The faults cannot be eliminated from the system but their occurance can be minimized while their effects can be minimized by improving the system design, quality of the equipment used and maintenance.

1.4 Causes, Nature and Effects of Faults in Power System

AU : Dec.-07,10,15,22, May-11,18,19

Generally a fault occurs due to the failure of insulation of a conductor at one or more points or a conducting object comes in contact with the live part of the system or conductors of transmission lines comes in contact with each other or with the ground.

1.4.1 Causes of Faults

There are number of causes for the occurrence of a fault in a power system. Some of the possible causes of faults are,

i) Excessive internal and external stresses on the conductors

ii) Overvoltages due to switching surges iii) Severe lightning strokes

iv) Heavy winds, rains or snow fall v) Falling of trees on transmission lines

vi) Ageing of conductors vii) High changes in atmospheric temperatures

viii) Accidents of vehicles with towers or poles

ix) Chemical pollution x) Perching of birds on the lines

xi) Accidential short circuit due to strings, snakes etc.

Though a power system consists of generators, switchgear equipments, transformers, there is always possibility of occurance of a fault somewhere on the system. The maximum possibility of fault occurance is on transmission lines due to their greater lengths and exposure to the atmospheric conditions.

Most of these faults lead to short circuit condition due to which impedance of the short circuit path becomes very low and very large fault currents flow. Thus the evaluation of these fault currents under short circuit conditions is important from the point of view of design and selection of protective equipments and their arrangement in a system.

It may be necessary to know the frequency of the fault occurance on various parts of the system which help in designing suitable protection circuit. Following table gives us an idea as to how the faults are distributed in the various parts of the system.

Sr. No.	Equipment	% of total faults
1.	Overhead lines	50
2.	Switchgear	15
3.	Transformer	12
4.	Cables	10
5.	Miscellaneous	8
6.	Control equipment	3
7.	CTs and PTs	2

Table 1.4.1

It can be seen from the above table that maximum number of faults are occuring on overhead lines.

1.4.2 Nature of Faults

The faults are classified as, i) Symmetrical faults and ii) Unsymmetrical faults.

1. Symmetrical faults : The symmetrical fault occurs when all the three conductors of a three phase line are brought together simultaneously into a short circuit. This gives rise to heavy fault currents in all the lines. Such a fault may occur if there is breakdown of insulation between all the three lines. It is also called line to line to line (L-L-L) fault. These faults are most severe in nature. These faults rarely occurs in practice. The symmetrical faults give rise to equal fault currents in all the lines.

2. Unsymmetrical faults : A fault in a power system which gives unsymmetrical currents in the three lines with unequal displacements is called unsymmetrical fault.

The various types of unsymmetrical faults are,

a. Single line to ground fault (L-G) : In this fault there occurs a short circuit between one of the phases and the earth. This is most commonly occurring fault.

b. Double line to ground fault (L-L-G) : In this fault there is short circuit between any two phases and the earth. This occurs due to insulation breakdown between two phases and earth.

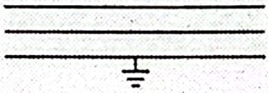
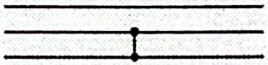
c. Line to line fault (L-L) : In this fault there is short circuit between any two phases.

d. Open circuit fault : In this fault there is open circuit in the lines due to breaking of lines due to accidents. This fault causes unbalanced currents to flow in the system.

A large number of these faults are transitory in nature. The word transitory refers to the fault which remains for short duration of time. The fault current varies with time. For example if a twig falls across a line and across arm and burns itself out or just falls down then the fault is transient as it vanishes after few cycles. During first one to three cycles, the fault current is very high but later on decreases very rapidly. This zone in which the current is very high but decreases very rapidly is called 'sub transient' state. After these first few cycles, the rate of current decrease is slower. This zone is called 'transient' state. This state remains for several cycles. After the transient state is over, steady state is reached. During the steady state, the rms value of short circuit current remains constant. The circuit breaker operates during transient state.

Most of the faults on power system are unsymmetrical in nature and most common type of fault is line to ground fault. The fault current produced by line to ground fault has considerable magnitude. So protective system must be properly designed so as to have reliable operation of relays under line to ground fault.

The various possible faults on power system are summarized in the Table 1.4.2.

Sr. No.	Type of fault	Representation	% occurance
1.	Line to Ground (L-G)		85
2.	Line to Line (L-L)		8

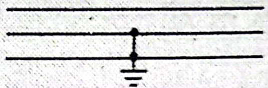
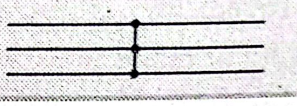
3.	Line to Line to Ground (L-L-G)		5
4.	Line to Line to Line (L-L-L)		2 or Less

Table 1.4.2

1.4.3 Effects of Faults

The various effects of faults in power system are,

1. The main effect of a fault is to set up very heavy fault current which is very large in magnitude which can damage the power system equipments.
2. The heavy currents produce overheating and high mechanical stresses.
3. There is always danger of fire due to arcing caused by heavy currents. If the fault persists for longer time then fire may spread to other parts of the system.
4. The overheating causes weakening of insulation of the conductors which reduces the life of insulation.
5. The unbalanced currents and voltages can cause heating of rotating machines connected to the system.
6. The generators interconnected in a system must operate in synchronism. Due to unbalanced currents and voltages due to fault, generators may lose synchronism causing total shutdown of the system. Thus the fault affects the system stability.
7. There may be interruption in the supply to the consumers thus reducing the reliability of the system.

Hence it is necessary to isolate the faulty part as quickly as possible from the healthy system using reliable protective devices.

Review Questions

1. *Discuss the nature and causes of faults in a power system.*

   AU : May-18, Dec.-07, Marks 6, Dec.-22, Marks 13

2. *Discuss the types of faults and their characteristics which occur in power system.*

   AU : Dec.-10, May-11, Marks 6

3. *Classify the different faults in power system. Which of these are more frequent ?*

   AU : Dec.-15, May-19, Marks 7

1.5 Protective Zones

AU : Dec.-06,10,12,15, May-11,18,19

In a protective relaying scheme, the circuit breakers are placed at the appropriate points such that any element of the entire power system can be disconnected for repairing work, usual operation and maintenance requirements and also under abnormal conditions like short circuits. Thus a protective covering is provided around each element of the system.

A **protective zone** is the separate zone which is established around each system element. The significance of such a protective zone is that any fault occurring within a given zone will cause the tripping of relays which causes opening of all the circuit breakers located within that zone. The various components which are provided with the protective zones are generators, transformers, transmission lines, bus bars, cables, capacitors etc. No part of the system is left unprotected. The Fig. 1.5.1 shows the various protective zones, used in a system.

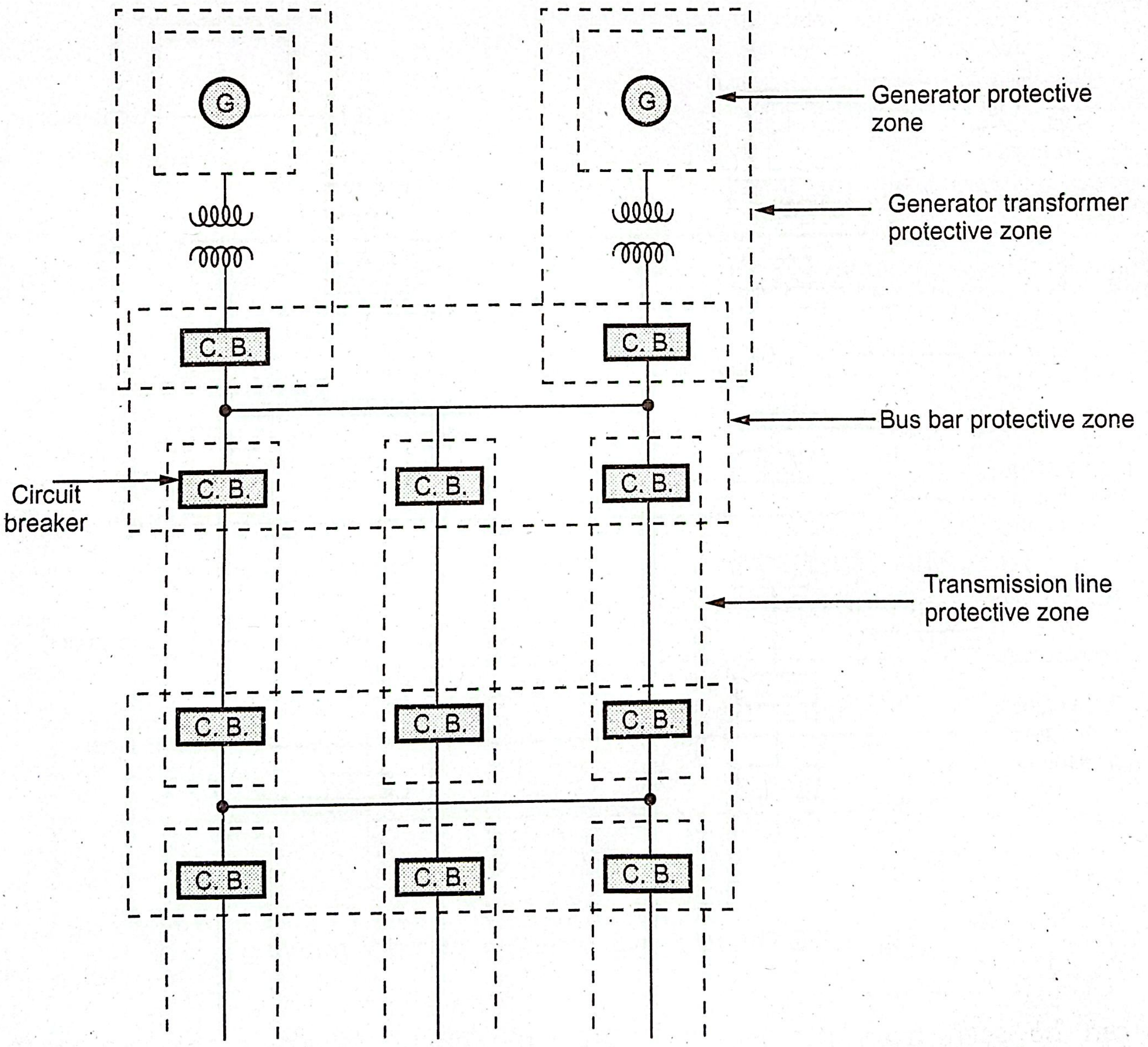

G
G
Generator protective zone
Generator transformer protective zone
C. B.
C. B.
Bus bar protective zone
Circuit breaker
C. B.
C. B.
C. B.
Transmission line protective zone
C. B.
C. B.
C. B.
C. B.
C. B.
C. B.

Fig. 1.5.1 Protective zones

The boundaries of protective zones are decided by the locations of the current transformers.

In practice, various protective zones are overlapped. The overlapping of protective zones is done to ensure complete safety of each and every element of the system. The zone which is unprotected is called dead spot. The zones are overlapped and hence there is no chance of existence of a dead spot in a system. For the failures within the region where two adjacent protective zones are overlapped, more circuit breakers get tripped than minimum necessary to disconnect the faulty element. If there are no overlaps, then dead spot may exist, means the circuit breakers lying within the zone may not trip eventhough the fault occurs. This may cause damage to the healthy system. The extent of overlapping of protective zones is relatively small. The probability of the failures in the overlapped regions is very low, consequently the tripping of too many circuit breakers will be also infrequent. The Fig. 1.5.2 shows the overlapping of protective zones in the primary relaying.

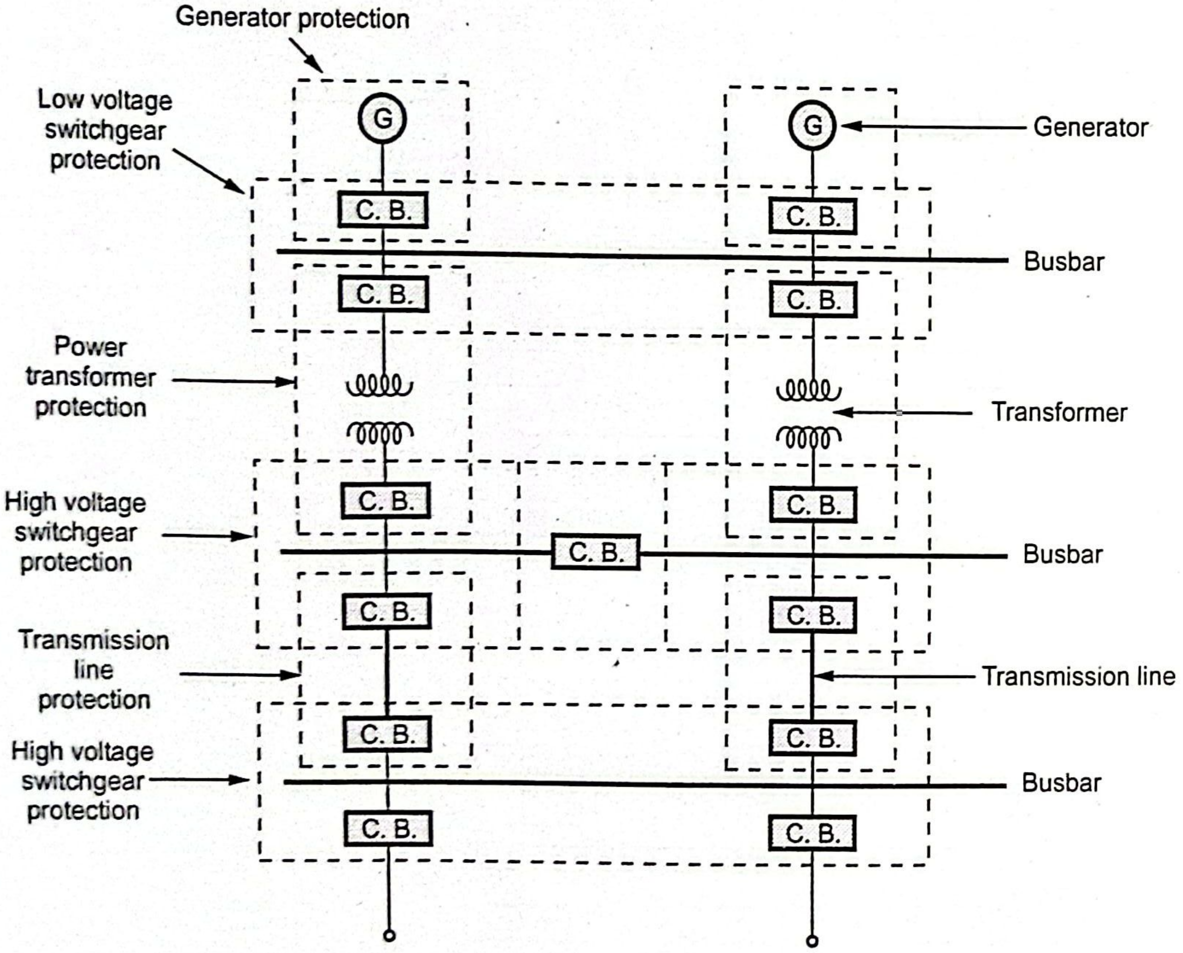

Generator protection
Low voltage switchgear protection
G
G
Generator
C. B.
Busbar
Power transformer protection
Transformer
High voltage switchgear protection
Busbar
Transmission line protection
Transmission line
High voltage switchgear protection
Busbar

Fig. 1.5.2 Overlapping zones in primary relaying

It can be seen from the Fig. 1.5.2 that the circuit breakers are located in the connections to each power system element. This provision makes it possible to disconnect only the faulty element from the system. Ocassionally for economy in the number of circuit breakers, a breaker between the two adjacent sections may be omitted but in that case both the power system sections are required to be disconnected for the failure in either of the two.

Each protective zone has certain protective scheme and each scheme has number of protective systems.

In practice, the protective zones are so designed that no area remains unprotected. The area which remains unprotected such that any fault occurring in that area would not be cleared at all is called **blind spot** of the power system. In blind spots, there is absence of relay output under fault conditions. To avoid the blind spots, the overlapping of zones is provided from complete protection point of view.

Review Questions

1. *Discuss the role of protective relaying and protective zones in a modern power system.*
AU : Dec.-12, Marks 8

2. *What do you understand by a zone of protection ? Discuss various zones of protection with neat diagram.*
AU : May-11,18, Dec.-06,10,12, Marks 8

3. *Explain the overlapping of protective zones with neat sketch.*
AU : Dec.-15, May-19, Marks 8

1.6 Primary and Backup Protection

AU : May-04,07,11,13,17,22, Dec.-18

The protection provided by the protective relaying equipment can be categorised into two types as :

1. Primary protection
2. Backup protection.

The primary protection is the first line of defence and is responsible to protect all the power system elements from all the types of faults. The backup protection comes into play only when the primary protection fails.

The backup protection is provided as the main protection can fail due to many reasons like,

1. Failure in circuit breaker
2. Failure in protective relay
3. Failure in tripping circuit
4. Failure in d.c. tripping voltage
5. Loss of voltage or current supply to the relay

Thus if the backup protection is absent and the main protection fails then there is a possibility of severe damage to the system.

When the primary protection is made inoperative for the maintenance purpose, the backup protection acts like a main protection. The arrangement of backup protective scheme should be such that the failure in main protection should not cause the failure in backup protection as well. This is satisfied if backup relaying and primary relaying do not have anything common. Hence generally backup protection is located at different stations from the primary protection. From the cost and economy point of view, the backup protection is employed only for the protection against short circuit and not for any other abnormal conditions.

1.6.1 Concept of Backup Relaying

Consider the backup relaying employed for the transmission line section EF as shown in the Fig. 1.6.1.

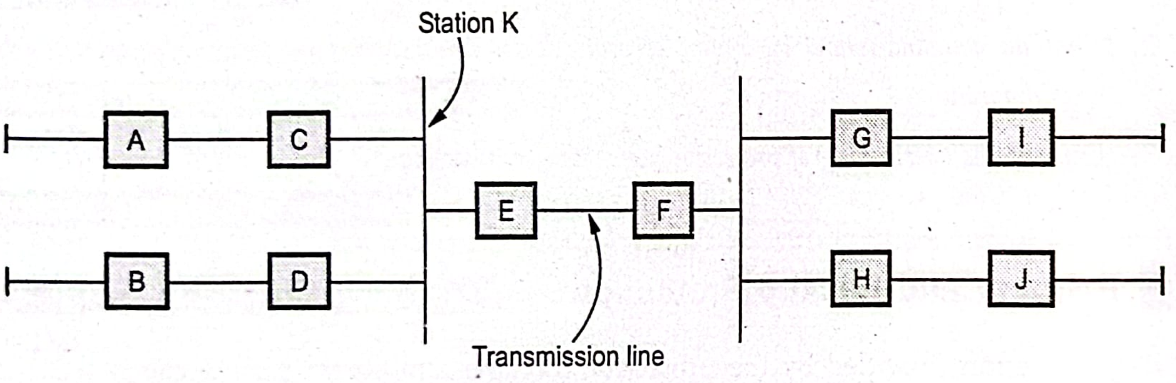


Fig. 1.6.1 Backup relaying

The relays C, D, G and H are primary relays while A, B, I and J are the backup relays.

Normally backup relays are tripped if primary relay fails. So if the primary relay E fails to trip, then backup relays A and B get tripped. The backup relays and associated backup relaying equipments are physically apart from the faulty equipment.

The backup relays A and B provide backup protection for fault at station K. Also the backup relays at A and F provide the backup protection for the faults in line DB.

The backup relaying often provides primary protection when the primary relays are out of service for repairs.

It is obvious that when the backup relay operates, the larger part of the system is disconnected.

The important requirement of backup relaying is that it must operate with sufficient time delay so that the primary relaying is given a chance to operate. When fault occurs, both the type of relays starts relaying operation but primary is expected to trip first and backup will then reset without having had time to complete its relaying operation.

When the given set of relays provides the backup protection for several adjacent system elements then the slowest primary relaying of any of those will determine the necessary time delay of the given backup relays.

1.6.2 Methods of Backup Protection

The various methods used for the backup protection are classified as,

1. **Relay backup protection :** In this scheme, a single breaker is used by both primary as well as backup protection but the two protective systems are different.
2. **Breaker backup protection :** In this method, separate breakers are provided for primary and backup protection. Both the types of breakers are at the same station.
3. **Remote backup protection :** In this method, separate breakers are provided for primary and backup protection. The two types of breakers are at the different stations and are completely isolated and independent of each other.
4. **Centrally co-ordinated backup protection :** In this method, primary protection is at various stations. There is a central control room and backup protection for all the stations is at central control room. Central control continuously inspects the load flow and frequency in the system. If any element of any part of the system fails, load flow gets affected which is sensed by the control room. The control source consists of a digital computers which decides the proper switching action. The method is also called centrally controlled backup protection.

Review Questions

1. *Explain primary and backup protection.* **AU : May-07, Dec.-18, Marks 8**
2. *Explain the methods of backup protection.* **AU : May-04, Marks 4**
3. *Explain the various protection schemes used in power system.* **AU : May-11,13,17, Marks 5**
4. *Explain the concept of back up relay and the methods of back-up protection.* **AU : May-22, Marks 13**

1.7 Essential Qualities and Requirements of Protective Relaying

AU : Dec.-07,10,11,14,16,17,18, May-07,08,12,14,19

A protective relaying scheme should have certain important qualities. Such an essential qualities of protective relaying are,

1. Reliability
2. Selectivity and discrimination
3. Speed and time
4. Sensitivity
5. Stability
6. Adequateness
7. Simplicity and economy.

1.7.1 Reliability

A protective relaying should be reliable is its basic quality. It indicates the ability of the relay system to operate under the predetermined conditions. There are various components which go into the operation before a relay operates. Therefore every component and circuit which is involved in the operation of a relay plays an important role. The reliability of a protection system depends on the reliability of various components like circuit breakers, relays, current transformers (C.T.s), potential transformers (P.T.s), cables, trip circuits etc. The proper maintenance also plays an important role in improving the reliable operation of the system. The reliability cannot be expressed in the mathematical expressions but can be judged from the statistical data. The statistical survey and records give good idea about the reliability of the protective system. The inherent reliability is based on the design which is based on the long experience. This can be achieved by the factors like,

i) Simplicity	ii) Robustness
iii) High contact pressure	iv) Dust free enclosure
v) Good contact material	vi) Good workmanship
vii) Careful maintenance.	

1.7.2 Selectivity and Discrimination

The selectivity is the ability of the protective system to identify the faulty part correctly and to disconnect that part without affecting the rest of the healthy part of system. The discrimination means to distinguish between. The discrimination quality of the protective system is the ability to distinguish between normal condition and abnormal condition and also between abnormal condition within protective zone and elsewhere. The protective system should operate only at the time of abnormal condition and not at the time of normal condition. Hence it must clearly discriminate between normal and abnormal condition. Thus the protective system should select the faulty part and disconnect only the faulty part without disturbing the healthy part of the system.

The protective system should not operate for the faults beyond its protective zone. For example, consider the portion of a typical power system shown in the Fig. 1.7.1.

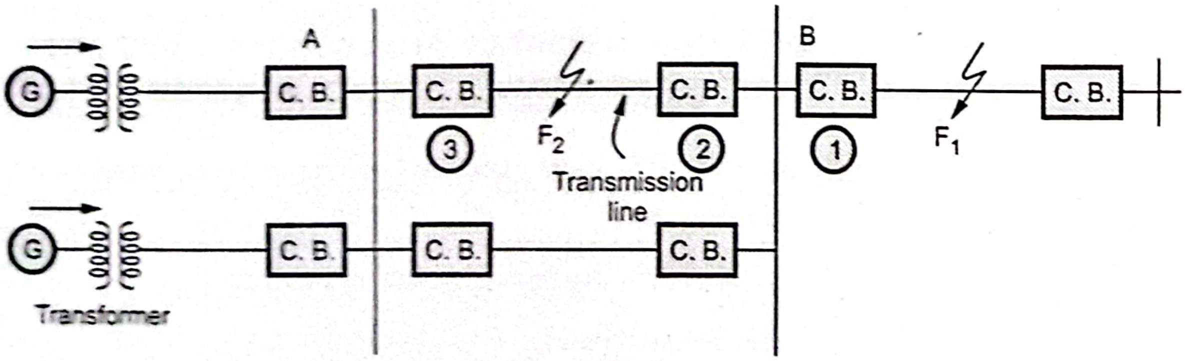


Fig. 1.7.1

It is clear from the Fig. 1.7.1 that if fault F_2 occurs on transmission line then the circuit breakers 2 and 3 should operate and disconnect the line from the remaining system. The protective system should be selective in selecting faulty transmission line only for the fault F_2 and it should isolate it without tripping the adjacent transmission line breakers or the transformer.

If the protective system is not selective then it operates for the faults beyond its protective zones and unnecessary the large part of the system gets isolated. This causes a lot of inconvenience to the supplier and users.

1.7.3 Speed and Time

A protective system must disconnect the faulty system as fast as possible. If the faulty system is not disconnected for a long time then,

1. The devices carrying fault currents may get damaged.
2. The failure leads to the reduction in system voltage. Such low voltage may affect the motors and generators running on the consumer side.
3. If fault persists for long time, then subsequently other faults may get generated.

The high speed protective system avoids the possibility of such undesirable effects.

The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is called fault clearing time. It is the sum of relay time and circuit breaker time. The relay time is the time between the instant of fault occurrence and the instant of closure of relay contacts. The circuit breaker time is the time taken by the circuit breaker to operate to open the contacts and to extinguish the arc completely. The fault clearing time should be as small as possible to have high speed operation of the protective system.

Though the small fault clearing time is preferred, in practice certain time lag is provided. This is because,

1. To have clear discrimination between primary and backup protection.
2. To prevent unnecessary operation of relays under the conditions such as transients, starting inrush of current etc.

Thus fast protective system is an important quality which minimises the damage and it improves the overall stability of the power system.

1.7.4 Sensitivity

The protective system should be sufficiently sensitive so that it can operate reliably when required. The sensitivity of the system is the ability of the relay system to operate with low value of actuating quantity.

It indicates the smallest value of the actuating quantity at which the protection starts operating in relation with the minimum value of the fault current in the protected zone.

The relay sensitivity is the function of the volt-amperes input to the relay coil necessary to cause its operation. Smaller the value of volt-ampere input, more sensitive is the relay. Thus 1 VA input relay is more sensitive than the 5 VA input relay.

Mathematically the sensitivity is expressed by a factor called sensitivity factor K_S. It is the ratio of minimum short circuit current in the protected zone to the minimum operating current required for the protection to start.

$$K_S = \frac{I_S}{I_o}$$

Where K_S = Sensitivity factor

I_S = Minimum short circuit current in the zone

I_o = Minimum operating current for the protection

1.7.5 Stability

The stability is the quality of the protective system due to which the system remains inoperative and stable under certain specified conditions such as transients, disturbance, through faults etc. For providing the stability, certain modifications are required in the system design. In most of the cases time delays, filter circuits, mechanical and electrical bias are provided to achieve stable operation during the disturbances.

1.7.6 Adequateness

There are variety of faults and disturbances those may practically exists in a power system. It is impossible to provide protection against each and every abnormal condition which may exist in practice, due to economical reasons. But the protective system must provide adequate protection for any element of the system. The adequateness of the system can be assessed by considering following factors,

1. Ratings of various equipments.
2. Cost of the equipments.
3. Locations of the equipments.
4. Probability of abnormal condition due to internal and external causes.
5. Discontinuity of supply due to the failure of the equipment.

1.7.7 Simplicity and Economy

In addition to all the important qualities it is necessary that the cost of the system should be well within limits. In practice sometimes it is not necessary to use ideal protection scheme which is economically unjustified. In such cases compromise is done. As a rule, the protection cost should not be more than 5 % of the total cost. But if the equipments to be protected are very important, the economic constraints can be relaxed.

The protective system should be as simple as possible so that it can be easily maintained. The complex system are difficult from the maintenance point of view. The simplicity and reliability are closely related to each other. The simpler systems are always more reliable.

Review Question

1. *Describe the essential qualities of a protective relaying.*

AU : Dec.-07,10,11,14,16,17,18, May-07,08,12,14,19, Marks 8

1.8 Terminologies used in Protective Relaying

AU : May-12

The various terminologies used in the protective relaying are,

1. Protective relay : It is an electrical relay, which closes its contacts when an actuating quantity reaches a certain preset value. Due to closing of contacts, relay initiates a trip circuit of circuit breaker or an alarm circuit.

2. Relay time : It is the time between the instant of fault occurrence and the instant of closure of relay contacts.

3. Breaker time : It is the time between the instant at circuit breaker operates and opens the contacts, to the instant of extinguishing the arc completely.

4. Fault clearing time : The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is fault clearing time. It is sum of the relay time and circuit breaker time.

5. Pickup : A relay is said to be picked up when it moves from the 'OFF' position to 'ON' position. Thus when relay operates it is said that relay has picked up.

6. Pickup value : It is the minimum value of an actuating quantity at which relay starts operating. In most of the relays actuating quantity is current in the relay coil and pickup value of current is indicated along with the relay.

7. Dropout or reset : A relay is said to dropout or reset when it comes back to original position i.e. when relay contacts open from its closed position. The value of an actuating quantity current or voltage below which the relay resets is called **reset value** of that relay.

8. Time delay : The time taken by relay to operate after it has sensed the fault is called time delay of relay. Some relays are instantaneous while in some relays intentionally a time delay is provided.

9. Sealing relays or holding relays : The relay contacts are designed for light weight and hence they are therefore very delicate. When the protective relay closes its contacts, it is relieved from other duties such as time lag, tripping etc. These duties are performed by auxiliary relays which are also called sealing relays or holding relays.

10. Current setting : The pick up value of current can be adjusted to the required level in the relays which is called current setting of that relay. It is achieved by use of tappings on the relay coil, which are brought out to a plug bridge as shown in the Fig. 1.8.1. The tap values are expressed interms of percentage full load rating of current transformer (C.T.) with which relay is associated.

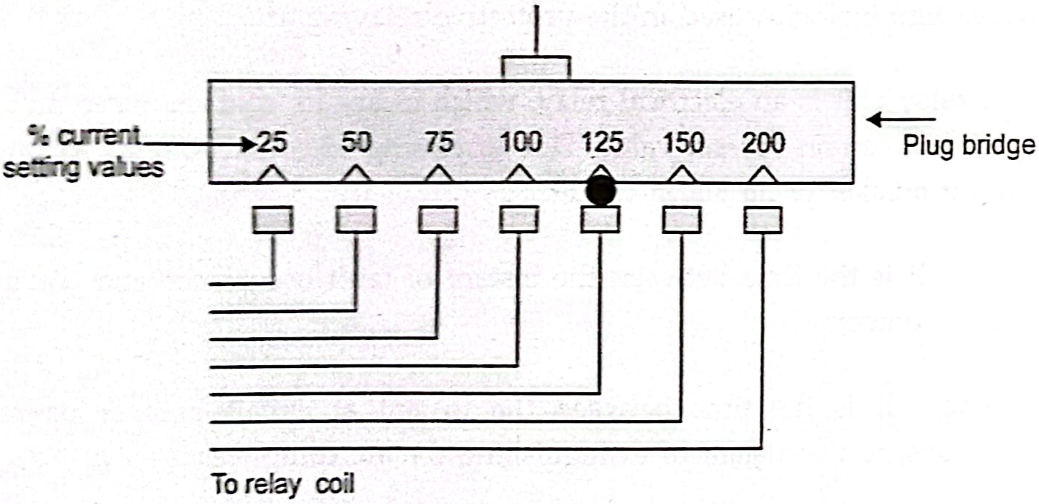


Fig. 1.8.1 Tapping for current setting

Thus the value of pickup current can be obtained as,

$$\text{Pickup current} = \% \text{ current setting} \times \text{Rated secondary current of C.T.}$$

So if C.T. is 500/10 A i.e. rated secondary current is 10 A and the current setting is 150 then pickup current is 1.5 × 10 = 15 A i.e. 150 % of 10. So when relay coil current is greater than or equal to pickup values, relay operates.

11. Plug setting multiplier (P.S.M.) : The ratio of actual fault current in the relay coil to the pickup current is called plug setting multiplier (P.S.M.) Mathematically it can be expressed as,

$$\text{P.S.M.} = \frac{\text{Fault current in relay coil}}{\text{Pickup value}} = \frac{\text{Fault current in relay coil}}{\text{\% current setting} \times \text{Rated secondary current of C.T.}}$$

12. Time/P.S.M. curve : For a relay, a curve showing relation between time and plug-setting multiplier is provided which is called time/P.S.M. curve. A typical curve for a relay is shown in the Fig. 1.8.2.

It can be observed that for low values of overcurrents the operating time varies inversely with the current. But as the current increases and approaches upto 20 times its rated value then the time becomes almost constant. This type of characteristics is necessary to ensure discrimination on very high fault currents flowing through healthy part of the system.

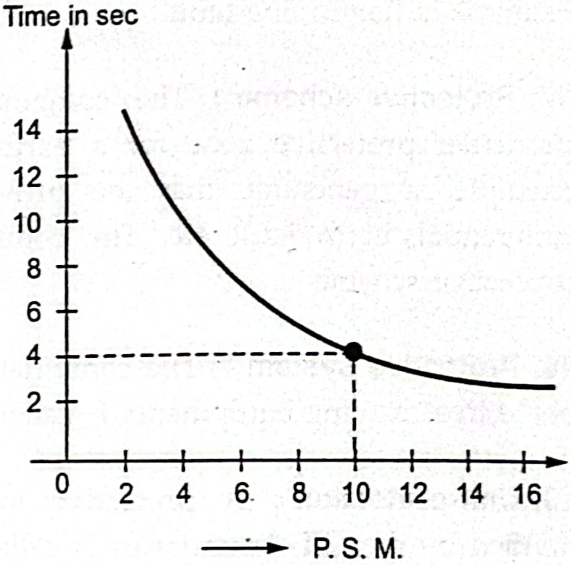


Fig. 1.8.2 Time / P.S.M. curve

Using this curve and time-setting multiplier, the actual time of operation of a relay can be obtained. For example, the time in seconds corresponding to P.S.M. of 10 is 4 seconds as shown in the Fig. 1.8.2. Multiplying this by a time-setting multiplier, actual time of operation can be obtained.

13. Time-setting multiplier : Similar to current setting, a relay is provided with a feature with which its time of operation can be controlled. This feature is known as time-setting multiplier. Its dial is calibrated from 0 to 1 in steps of 0.05 as shown in the Fig. 1.8.3.

The value of time-setting multiplier along with the time obtained from time/P.S.M. curve decides the actual time of operation of the relay. For example if time-setting multiplier is selected as 0.2 while time corresponding to P.S.M. of 10 is 4 seconds then,

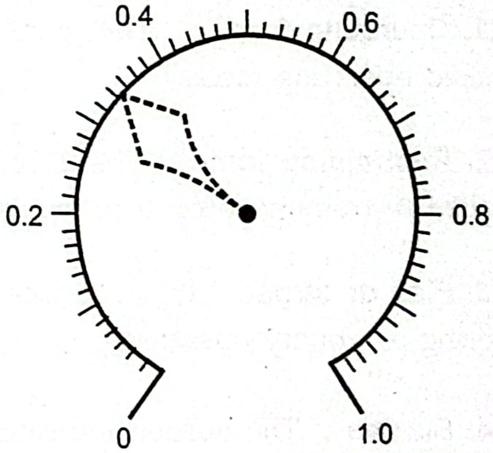


Fig. 1.8.3 Time-setting multiplier

$$\text{Actual time of operation} = \text{Time in seconds} \times \text{Time-setting multiplier}$$
$$= 4 \times 0.2 = 0.8 \text{ seconds}$$

14. Trip circuit : The opening operation of circuit breaker is controlled by a circuit which consists of trip coil, relay contacts, auxiliary switch, battery supply etc. which is called trip circuit.

15. Earth fault : The fault involving earth is called earth fault. The examples of earth fault are single line to ground fault, double line to ground fault etc.

16. Phase fault : The fault which dies not involve earth is called phase fault. The example is line to line fault.

17. Protective scheme : The combination of various protective systems covering a particular protective zone for a particular equipment is called protective scheme. For example, a generator may be provided with protective systems like overcurrent, differential, earth fault etc. The combination of all these systems is called generator protective scheme.

18. Protective system : The combination of circuit breakers, trip circuits, C.T. and other protective relaying equipments is called protective system.

19. Unit protection : A protective system in which the protection zone is clearly defined by the C.T. boundaries is called unit protection. Such systems work for internal faults only.

20. Reach : The limiting distance in which protective system responds to the faults is called reach of the protective system. The operation beyond the set distance is called over-reach while failure of distance relay within set distance is called under-reach.

21. Operating force : The force or a torque which tends to close the relay contacts is called operating force.

22. Restraining force : The force or a torque which opposes the operating force is called restraining force. It prevents the closing of the relay contacts.

23. Flag or target : It is a device which is used to indicate the operation of a relay. It is spring or gravity operated.

24. Burden : The burden indicates the power consumption of the relay circuit elements. It is the power absorbed by the relay circuit elements, expressed in volt-amperes (VA) for a.c. and in watts (W) for d.c. circuits, under the rated current and voltage conditions.

25. Interlock : The system used in the protection to speed up the tripping for some faults, without sacrificing the co-ordination of system and avoiding malfunctioning of the trips.

26. Blind spot : If some part of the system remains unprotected then any fault occurring in this area would not be cleared at all. Such an area is called blind spot.

27. Auto reclosing : The faults on a power system are of three types namely transient, semi-permanent and permanent. The transient faults are frequent and occur for short period of time. If the system is isolated momentarily till the arc gets extinguished, such faults disappear. Hence practically such systems are restored automatically by reclosing the circuit breakers used to isolate the system. This automatic feature of reclosing the contacts is called auto reclosing.

28. Operating time : The time which elapses from the instant when the actuating quantity reaches a value equal to pick-up value upto the relay operates its contacts is called operating time.

29. Reset time : The time which elapses between the instant when the actuating quantity value becames less than the reset value upto the instant when relay contacts return to the normal position is called reset time.

Review Questions

1. *Explain the following terms related to protective relaying :*

i) Pickup	*ii) Dropout or reset*	*iii) Time delay*
iv) Holding relay	*v) Trip circuit*	*vi) Protective scheme*
vii) Protective system	*viii) Current setting*	*ix) Plug-setting multiplier*
x) Time-setting multiplier.		

2. *Define the terms : i) Pick up value ii) Operating time iii) Seal-in relay iv) Burden.*
3. *Define the terms pick up value, plug setting multiplier and auto reclosing.*

AU : May-12, Marks 6

1.9 Introduction to Power System Earthing

The earthing or grounding is nothing but the connection of neutral point of the supply system to the general mass of earth in such a way that immediate discharge of electricity can take place without danger.

When grounding is provided then it ensures the safety of personnel against electrical shocks and avoids accidents. The equipment is also protected against lightning and voltage surges. The voltage stress on lines is reduced along with that on the equipments with respect to earth under abnormal conditions. With earthing, the earth fault currents are controlled for protective relays.

There are two ways in which the three phase systems can be operated. These are viz. with isolated neutral and with earthed neutral.

But presently isolated neutral system is not used as with such system during fault, large transient voltages with magnitude several times that of normal value is produced which may cause breakdown of insulation. This results in damage of the concerned equipment and interruption of the supply system. Inspite of this the advantage of this system is under earth fault on one of the phases, the remaining two healthy phases will continue supplying load for a shorter period.

1.10 Earthed Neutral System

AU : Dec.-08,16, May-18

In this system, the neutral is earthed either directly or through resistance or reactance depending on the requirement. Thus the system neutral can be grounded effectively or non-effectively. In effectively grounded system, the neutral is grounded directly and hence it is called solid grounding. While the methods in which neutral is not directly grounded are called non-effectively grounded systems.

The **advantages of neutral earthing** are as follows,

i) The arcing grounds are prevented from occuring by employing suitable switchgears.

ii) As the neutral point is not shifted in this system, thus the voltages of healthy phases remains nearly constant.

iii) The static charges which are induced are grounded immediately and are thus prevented from causing any disturbance.

iv) The faulty part of the system can be isolated from the remaining system with the help of earth fault relays.

v) The magnitude of transient voltage is small in this system.

vi) The discriminative type fault indicator can be installed on such systems.

vii) This system is more reliable, provides safety to personnel and equipment with reduced operational and maintenance cost than ungrounded system.

Review Questions

1. *What are the advantages of neutral earthing ?* **AU : Dec.-08, Marks 4**
2. *What is the need of earthing ?* **AU : Dec.-16, May-18, Marks 4**

1.11 Methods of Neutral Grounding

AU : May-12,13,15,17,18,19,22, Dec.-04,06,07,12,14,15,16,17,18,22

The various methods used for neutral grounding in a power system are,

i) Solid grounding ii) Resistance earthing

iii) Reactance earthing

iv) Arc suppression coil or resonant grounding

v) Using earthing transformer

vi) Voltage transformer earthing

1.11.1 Solid Grounding

In this method of earthing, neutral is directly connected to earth by a metallic connection or a wire of negligible resistance and reactance. The charging currents flow through the system under normal condition similar to ungrounded system.

Because of the connection of system neutral point to earth, it always remains at earth potential at all operating conditions and under faulty conditions voltage of healthy phase will not exceed.

The solid grounding is represented in the Fig. 1.11.1.

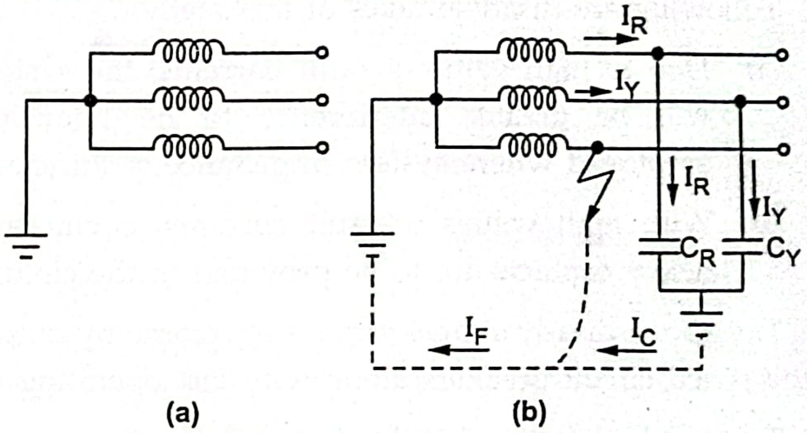


Fig. 1.11.1 Solid earthing

Whenever there is earth fault on any one phase (phase B in this case), the phase to earth voltage of faulty phase is zero while voltage to earth of the remaining two healthy phases will be normal phase voltages as neutral in this case is not shifted. The phasor diagram corresponding to this condition is shown in the Fig. 1.11.2.

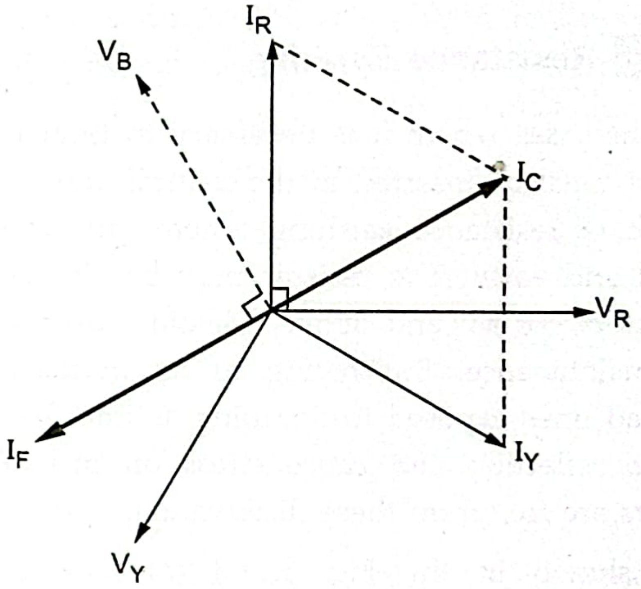


Fig. 1.11.2 Phasor diagram

Let the capacitive currents flowing in the healthy phases be I_R and I_Y. the resultant capacitive current is vector sum of I_R and I_Y. The alternator in addition to capacitive current also provides the fault current I_F. This current flows from fault point through faulty phase and then return to the alternator through earth and neutral connection. The resistance of earth fault is negligible. The magnitude of fault current after the analysis is given by,

$$I_F = \frac{3V_{ph}}{Z_1+Z_2+Z_0}$$

This current is mainly dependent on zero sequence impedance of the source of power and that of phase conductor upto fault point. As the resistive component of zero sequence impedance is normally negligible, the fault current which is large can be assumed as lagging the faulty phase voltage by 90°. From the phasor diagram, it can be seen that I_F and I_C are exactly opposite due to which capacitive current is neutralised by high fault current which eliminates the possibility of arcing grounds and overvoltages. The discriminative types of switchgears may be used in this method.

Following are disadvantages of this method,

i) Due to high value of fault currents, the system may become unstable and there will be greater interference to neighbouring circuits. Thus this method is employed where system impedance is sufficiently large to limit fault current.

ii) With high values of fault currents, circuit breakers are difficult to handle and heavy contacts are to be provided in the circuit breakers.

The above disadvantages can be overcome by employing high rupturing capacity and high speed circuit breakers along with fast operating relays.

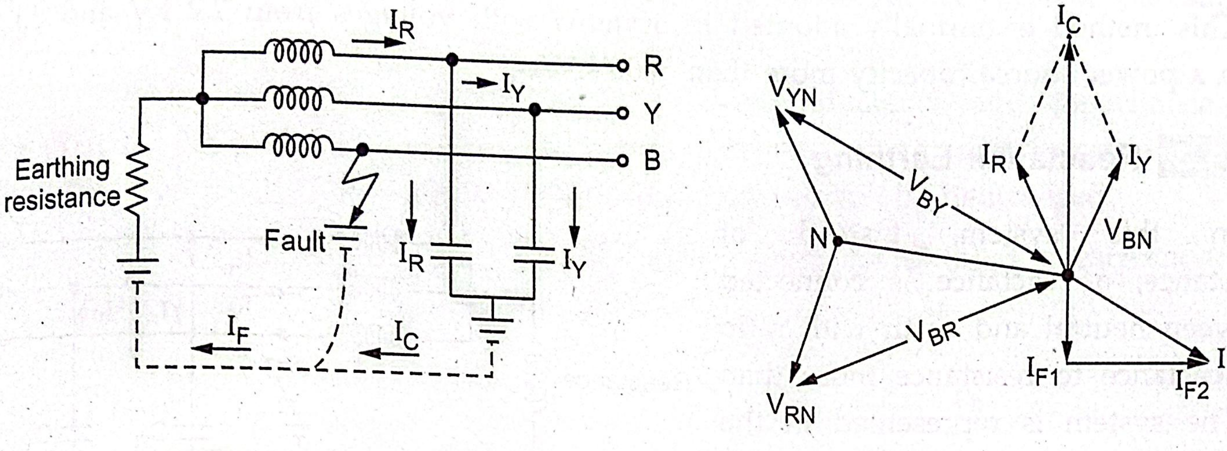
This method is used in high voltage systems with voltages below 33 kV with total capacity not exceeding 5000 kVA for the economic reasons.

1.11.2 Resistance Earthing

In the cases where it is necessary to limit the fault current then the current limiting element must be inserted in the neutral and earth. One of the ways of achieving this is the use of resistance earthing where one or more resistances are connected between neutral and earth. The resistor may be either of wire or water column resistances for voltages of 6.6 kV and above. Metallic resistors do not change with time and requires little maintenance. But owing to its inductive nature they have disadvantage with overhead lines exposed to lightning as impulses or the travelling waves are subjected to positive reflection and cause stress on insulation resulting in its breakdown. Liquid resistors are free from these disadvantages and have simple and robust construction.

As shown in the Fig. 1.11.3 (a) let the earth fault occurs on phase B. The corresponding phasor diagram is shown in the Fig. 1.11.3 (b). The capacitive currents I_R and I_Y flow through the healthy lines. The fault current not only depends on the zero sequence impedance of the source but also on the resistance in the earth circuit. This fault current can be resolved into two components one inphase with the faulty phase voltage and other lagging the faulty phase voltage by 90°. This lagging component of current is in phase opposition to capacitive current and it varies with change in value of earthing resistance. Thus the value of this resistance is designed in such a way that during fault on any phase, a current equal to full load current of largest alternator or transformer flows in earth resistance which will keep the overvoltages within limits.

With fault current lagging component equal to capacitive current the system operation is similar to solidly earth system and no transients occur due to arcing ground.



(a) Circuit representation **(b) Phasor diagram**

Fig. 1.11.3

With high value of earthing resistance and low value of reactive current than the capacitive current then system conditions approach to that of ungrounded system with chances of transient over voltages to occur. The line to earth voltage of the healthy phases at the time of fault is little more than line to earth voltage of the solidly grounded system operating under similar conditions. The duration of this voltage can be reduced by using suitable protective switchgears to avoid any harmful effect that may be caused.

The value of resistance to be inserted in earth circuit is given by,

$$\boxed{R = \frac{V_L}{\sqrt{3} \cdot I}}$$

where V_L = Line to Line voltage

I = Full load current of largest alternator or transformer

The advantages of this system are as follows,

1) The discriminative type of switchgears may be used for protection.

2) The hazards due to arcing grounds are minimized.

3) The influence on neighbouring communication circuits is minimized due to lower value of fault current flowing through earth as compared to that in case of solidly grounded system.

The disadvantages of this method are given below,

1) As the neutral is shifted during earth faults, the equipments are to be selected for greater voltages.

2) The system is expensive than the solidly grounded system.

3) There is energy loss in neutral grounding resistor for dissipation of fault energy.

This method is normally adopted in systems with voltages from 2.2 kV and 33 kV with a power source capacity more than 5000 kVA.

1.11.3 Reactance Earthing

In this system, instead of resistance, a reactance is connected between neutral and earth with ratio of reactance to resistance more than 3. The system is represented in the Fig. 1.11.4. Let the earth fault occurring on phase B.

In addition to zero sequence impedance of the source and faulty phase upto point of fault, the fault current is dependent on reactance. By changing the value of reactance, the fault current can be varied. In practice this method is employed to give characteristics similar to solidly earth system.

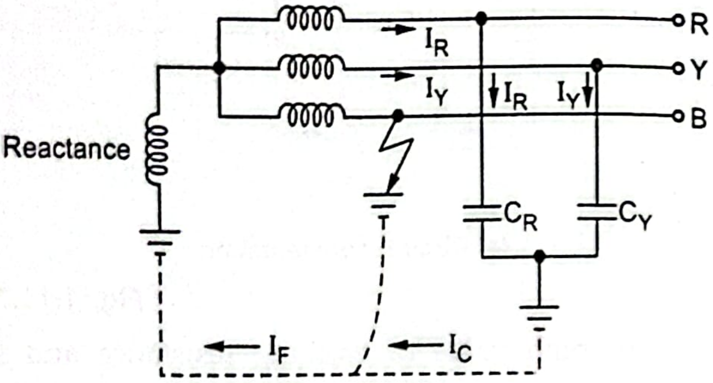


Fig. 1.11.4

There is drawback of this system. With increase in reactance, there is increase in transient voltages resulting from arcing. Hence it is not commonly employed though it ensures satisfactory relaying, partial grading of equipment insulation, less interference with neighbouring circuits, and intermediate cost.

For reactance earthing, it is necessary that the magnitude of fault current should be at least 25 % of the three phase fault current. This is higher than the requirement on resistance earthing and thus it can be seen that the resistance earthing and the reactance earthing are not similar.

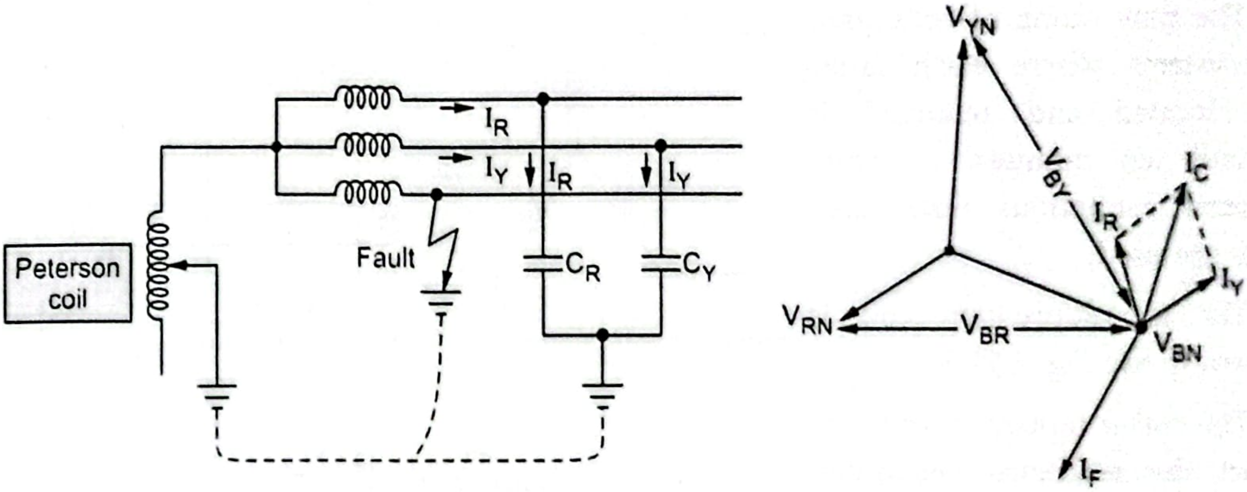
1.11.4 Arc Suppression Coil Grounding (Resonant Grounding)

This system is also referred to as arc suppression coil grounding. In the previous earthing methods that we have discussed the earth fault on any one of the phases causes total shut down of the system. So continuity of supply can not be maintained. This is not the case with ungrounded system where fault on one phase will not cause other phases to supply power. This method of grounding has this advantage of isolated neutral system along with reduced possibility of arcing grounds and numerous other advantages.

It consists of a coil called **Peterson coil or ground fault neutralizer or arc supression coil** whose function is to make arcing earth faults self extinguishing and in the case of sustained faults to reduce the earth current to low value so that system can supply power with one line earthed.

This system works on the principle that when inductance and capacitance are connected in parallel, resonance takes place between them and because of the characteristics of resonance, the fault current is reduced or can be neutralized.

The system with fault on phase B is shown in the Fig. 1.11.5 (a). The corresponding phasor diagram is shown in the Fig. 1.11.5 (b)



(a) Circuit representation (b) Phasor diagram

Fig. 1.11.5 Resonant grounding

An arc supression coil is an iron-cored reactor similar to oil immersed transformer connected between neutral of system and earth. This coil is provided with number of tappings so that it can be tuned with the capacitance which may vary due to varying operational conditions.

As the system operation is similar to isolated neutral system, the phase to earth voltage of healthy phase is $\sqrt{3}$ times the normal phase voltage and the resultant capacitive current is 3 times the normal charging current of one phase. The resultant capacitive current will lead by 90° with faulty phase voltage while the fault current lags by 90° with faulty phase voltage.

Now we have, $I_F = I_C$ at resonance, $I_F = \frac{V_{ph}}{X_L}$; $I_C = \frac{3\,V_{ph}}{X_C}$

$$\therefore \quad \frac{V_{ph}}{X_L} = \frac{3\,V_{ph}}{X_C} \quad \text{i.e.} \quad X_L = \frac{X_C}{3} \quad \text{i.e.} \quad \omega L = \frac{1}{3\omega C}$$

$$\therefore \quad \boxed{L = \frac{1}{3\omega^2 C}}$$

There is one problem with the above method. As the operating conditions vary, the capacitance of the network also vary. This can be overcome by using a tapped coil. The appropriate tapping is required to be used for each of the change in the network conditions. The current rating of the coil is given by,

$$\therefore \quad \boxed{I_F = \frac{3\,V_{ph}}{X_C}}$$

The time rating of coils used in systems where earth faults are located and removed is around ten minutes. In other systems continuous time rated coils are used.

The arc supression coil is shown in the Fig. 1.11.6.

The coil is tapped in order to select the reactance depending upon the length of transmission line and the capacitance to be neutralized. The arc supression coil is connected between neutral and ground.

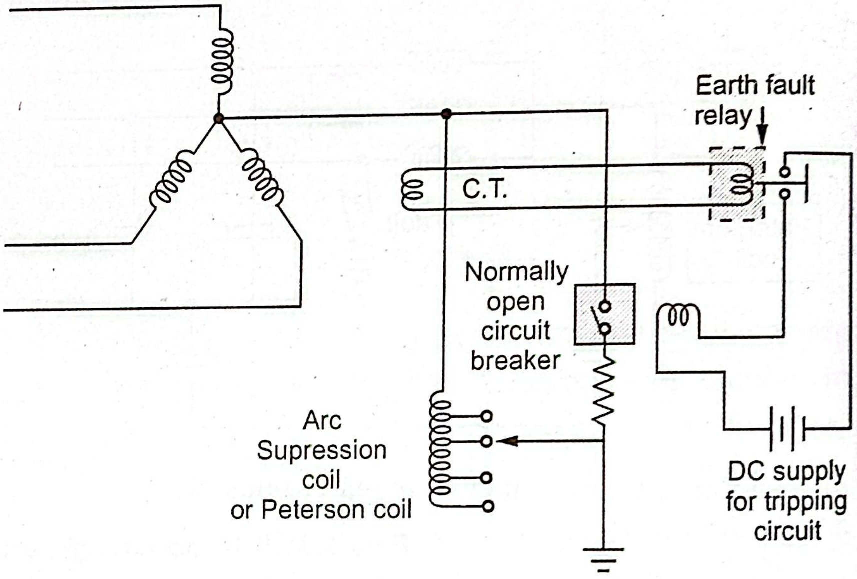

Earth fault relay
C.T.
Normally open circuit breaker
Arc Supression coil or Peterson coil
DC supply for tripping circuit

Fig. 1.11.6

The reactance of the coil can be evaluated by using the expression $L = \frac{1}{3\omega^2 C}$.

The rating of the coil is continuous and equal to the maximum earth fault current. If a double phase to ground fault or another ground fault occurs, the current flowing through the coil is more. This can be prohibited with closing of a circuit breaker after certain time lag. The earth fault current flows through the parallel circuit by passing the arc supression coil. Here the circuit breaker is normally open and closes after the closure of relay tripping circuit by passing arc supression coil.

This method of neutral grounding is used in medium voltage overhead transmission line which are connected to system generators through intermediate power transformers. This is because the higher insulation requirement on the apparatus associated with arc supression coil grounding system is easily incorporated in power transformers than in generators. Also the overhead lines are usually subjected to earth faults due to lightning. Hence protection is required.

Example 1.11.1 *A 132 kV, 3 phase, 50 cycles, overhead line, 50 km long has a capacitance to earth line of 0.0157 μF/km. Determine the inductance and kVA rating of the arc suppression coil.* **AU : Dec.-16, Marks 6**

Solution : $V_L = 132$ kV, $f = 50$ Hz, $C' = 0.0157\ \mu F/km$, $l = 50$ km ,

$$\omega = 2\pi f = 2\pi \times 50 = 314.159 \text{ rad/s.}$$

Capacitance of each line to earth = $C' \times l$

$$\therefore \quad C = 0.0157 \times 50 = 0.785\ \mu F$$

Inductance required for Peterson (arc suppression) coil is,

$$L = \frac{1}{3\omega^2 C} = \frac{1}{3 \times (314.159)^2 \times 0.785 \times 10^{-6}} = \mathbf{4.302\ H}$$

$$\text{Current through coil} = \frac{V_{ph}}{X_L} = \frac{V_L/\sqrt{3}}{\omega L}$$

$$= \frac{\left(\frac{132 \times 10^3}{\sqrt{3}}\right)}{314.159 \times 4.302}$$

$$\text{i.e.} \quad I_{ph} = 56.388 \text{ A}$$

$$\therefore \quad \text{kVA rating of coil} = V_{ph} I_{ph}$$

$$= \frac{132 \times 10^3}{\sqrt{3}} \times 56.388 = \mathbf{4297.34\ kVA}$$

Example 1.11.2 *In a 50 Hz overhead line, the capacitance of one line to earth was 1.6 μF. It was decided to use an earth fault neutralizer. Calculate the reactance to neutralize the capacitance of i) 100 % of the length of line ii) 90 % of the length of the line iii) 95 % of the length of the line.*

Solution : $\omega = 2\pi f = 2\pi \times 50 = 100\pi = 314.159$ r/s

$$C = 1.6\ \mu F = 1.6 \times 10^{-6} \text{ F}$$

i) For 100 % length of the line

We have inductance of Peterson coil given by,

$$L = \frac{1}{3\omega^2 C} = \frac{1}{3(314.159)^2(1.6 \times 10^{-6})} = 2.11 \text{ H}$$

Reactance $X_L = 2\pi fL = \omega L = (314.159)(2.11) = 663.14\ \Omega$

ii) Capacitance for 90 % of the length of the line is

$$1.6 \times 0.9 = 1.44\ \mu F = 1.44 \times 10^{-6}$$

$$\text{Inductance, } L = \frac{1}{3\omega^2 C} = \frac{1}{3(314.159)^2 (1.44 \times 10^{-6})} = 2.34\ H$$

Inductive reactance, $X_L = \omega L = (314.159)(2.34) = 736.82\ \Omega$

iii) Capacitance for 95 % of the length of the line is,

$$1.6 \times 0.95 = 1.52\ \mu F = 1.52 \times 10^{-6}$$

$$\text{Inductance, } L = \frac{1}{3\omega^2 C} = \frac{1}{3(314.159)^2 (1.52 \times 10^{-6})} = 2.22\ H = 2.22\ H$$

Inductive reactance, $X_L = \omega L = (314.159)(2.22) = 698.04\ \Omega$

1.11.5 Voltage Transformer Earthing

In this system of earthing, the neutral point is earthed through a single phase voltage transformer. The system thus acts as an insulated neutral system. A very high reactance earthing is provided due to the voltage transformer.

The connection diagram is shown in the Fig. 1.11.7.

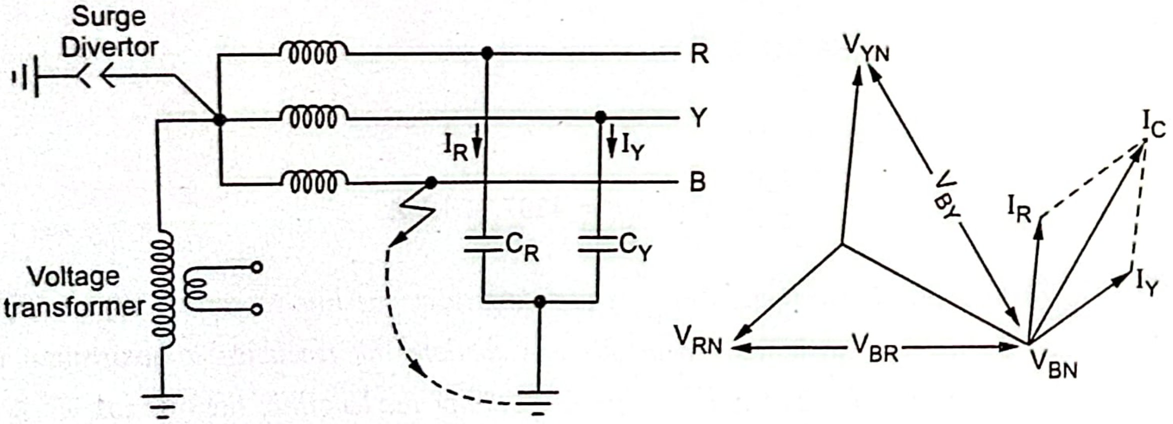


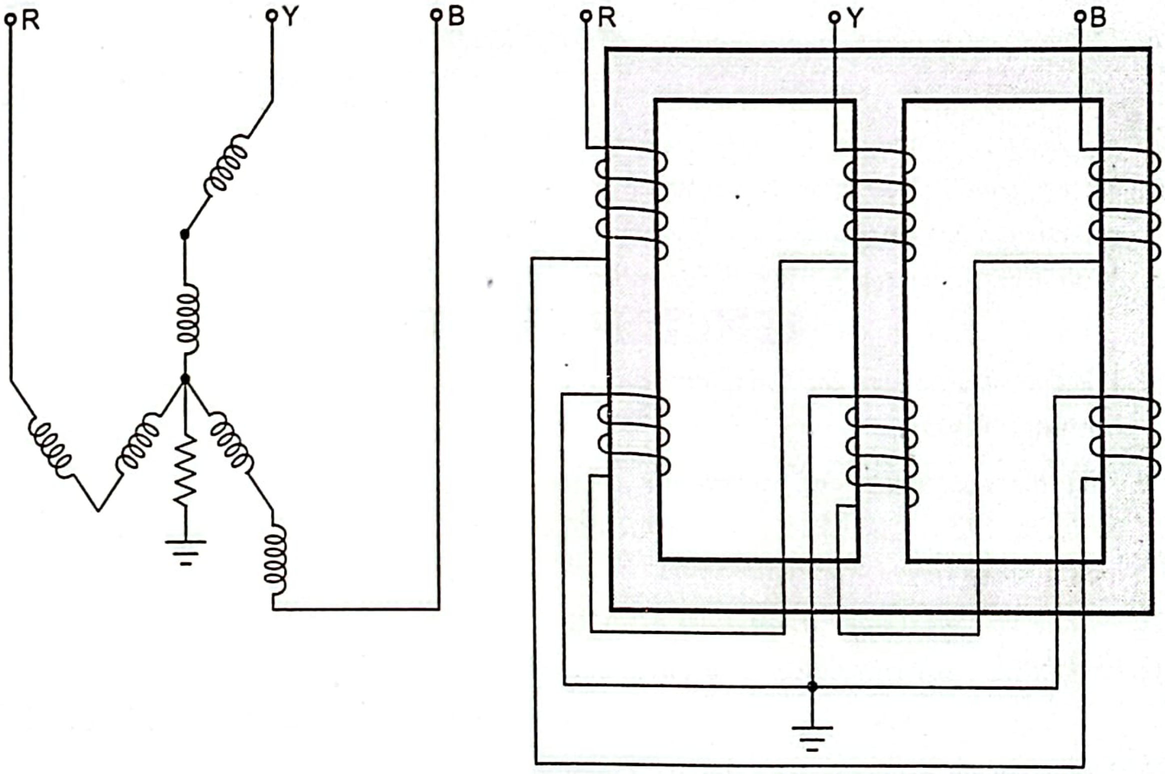
Fig. 1.11.7

The voltage transformer shown in the figure measures the voltage so that earth fault on the system is indicated. The travelling waves passing through the machine winding are reflected through voltage transformer. A surge divertor is used between neutral and earth to avoid the rise of voltage.

The voltage transformer is used normally in generator circuits which are directly connected to step up transformers. The generator circuits are physically isolated from the main distribution system. The electrostatic capacity of the circuit is negligible as the interconnecting cables between the generator and transformer windings are normally short. The risk of overvoltage conditions arising due to arcing ground is eliminated.

1.11.6 Earthing Transformer

When the transformers or generators are delta connected or if the neutral points are not accessible then artificially the neutral earthing point can be created with the use of star connected earthing transformer. Such transformer has no secondary. Each phase of primary has two equal parts. There are three limbs and each limb has two windings providing opposite flux during normal condition. Such a transformer is shown in the Fig. 1.11.8.



(a) Winding of an earthing transformer

(b) Schematic arrangement of winding of an interconnected star connected earthing transformer

Fig. 1.11.8

One set of windings are connected in star providing the neutral point. The other ends of this set of windings are connected to the second set of windings as shown in the Fig. 1.11.8. The directions of the currents in the two windings on each limb are opposite to each other. The small exciting current is circulated in the windings during normal operation. Under faulty condition, the transformer offers a low impedance path to the flow of zero phase sequence currents. The value of fault current is limited in some cases by the use of a resistor in series with the neutral earthing connection. This is necessary in systems with operating voltage between 2.2 kV and 3.3 kV.

These transformers are of short time ratings in the range of 10 seconds to 1 minute Hence the size of these transformers is small as compared to power transformers of same rating. If the earthing transformer is not available then a star-delta transformer is used.

Review Questions

1. *Write a short note on power system earthing.* **AU : May-13, Marks 5**
2. *Explain solid grounding.* **AU : Dec.-04, Marks 8**
3. *Explain resistance earthing.* **AU : Dec.-04, 18, Marks 8**
4. *Explain the reactance grounding.* **AU : Dec.-18, Marks 3**
5. *Write a note on resonant grounding.* **AU : Dec.-06, Marks 8**
6. *Derive the expression for the reactance of the Peterson coil.* **AU : Dec.-15, May-19, Marks 8**
7. *A 132 kV, 3-Phase, 50 Hz, 100 km long transmission line has a capacitance of 0.012 μF per km per phase. Determine the inductive reactance and kVA rating of the arc suppression coil suitable for this line.* **[Ans. : 2.8144 H, 6569.80]**
8. *With a neat diagram, explain the operating principle of Peterson coil or arc suppression coil.* **AU : May-12, 15, 17, Dec.-12, Marks 8; Dec.-07, 18, Marks 5**
9. *What is a Peterson coil? Explain the protective function performed by this device with necessary diagram.* **AU : Dec.-14, Marks 8**
10. *Find the inductance and capacitance of the arc suppression coil for a 132 kV, 3-phase, 50 hertz, 192 km line having 3 conductors of diameter 20 mm arranged in a vertical plane with 4 meter spacing.* **[Ans. : 1.716 μF, 1.9675 H]**
11. *Write a note on voltage transformer earthing.*
12. *Explain the various methods of earthing the neutral point of the power system.* **AU : Dec.-15,16,17, May-18, Marks 12**
13. *Briefly explain the methods of neutral grounding and discuss its advantages.* **AU : May-22, Marks 13**
14. *Explain the method of resistance and reactance grounding of the power system with neat sketch* **AU : Dec.-22, Marks 13**

1.12 Introduction to Insulation Co-ordination **AU : May-13,15, Dec.-13,14**

The electrical equipments are expected to provide service for more than 25 years. The insulators give support to conductors. The insulation system of an electrical equipment, which may be internal or external is often exposed to continuous normal operating voltages and abnormal overvoltages occasionally.

The insulation system is designed normally to withstand peak power frequency system voltage occasional temporary power frequency overvoltages, occasional lightning and/or switching surges reaching the equipment.

Let us consider the factors to be considered while deciding the insulation requirements.

1) The peak of normal operating power frequency voltage which the system is exposed to continuously

2) The temporary power frequency overvoltages lasting from few milliseconds to seconds due to thrown off loads, faults or resonance. This is shown in the Fig. 1.12.1.

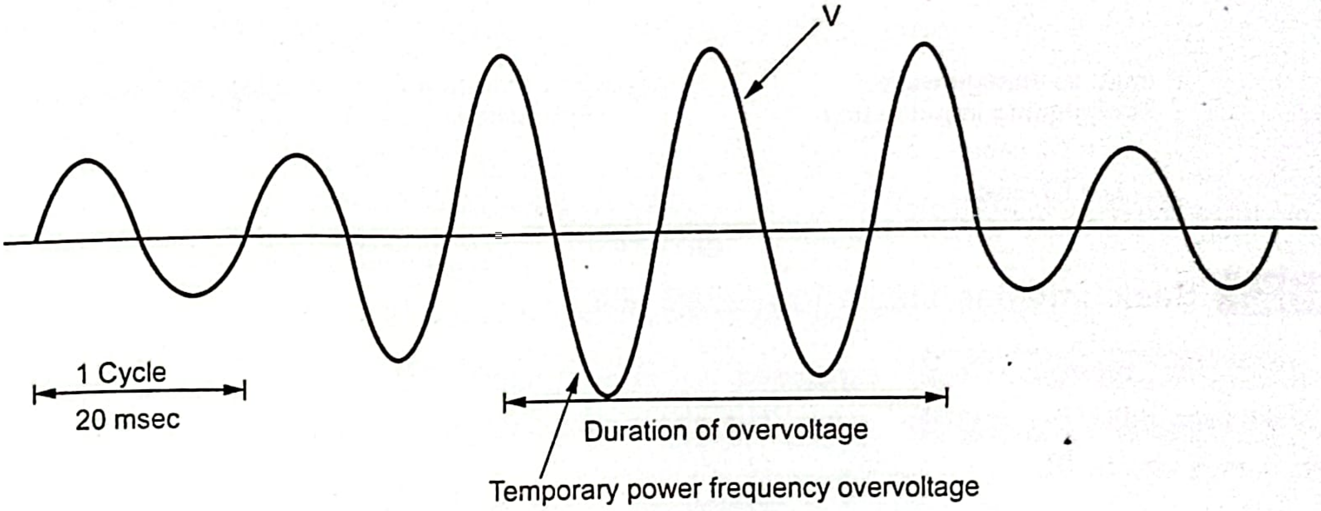
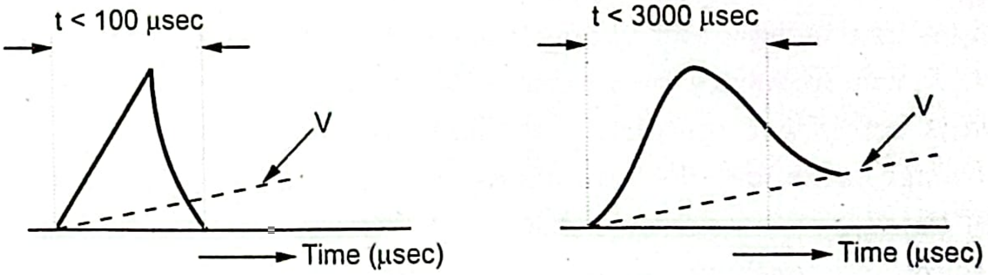

V
1 Cycle
20 msec
Duration of overvoltage
Temporary power frequency overvoltage

Fig. 1.12.1

3) The transient overvoltage surges which last for few hundred microseconds which are due to lightning, switching restrikes, travelling waves. The surges are intercepted by surge arresters and protect the equipment. The lightning surge and switching surge is shown in the Fig. 1.12.2.

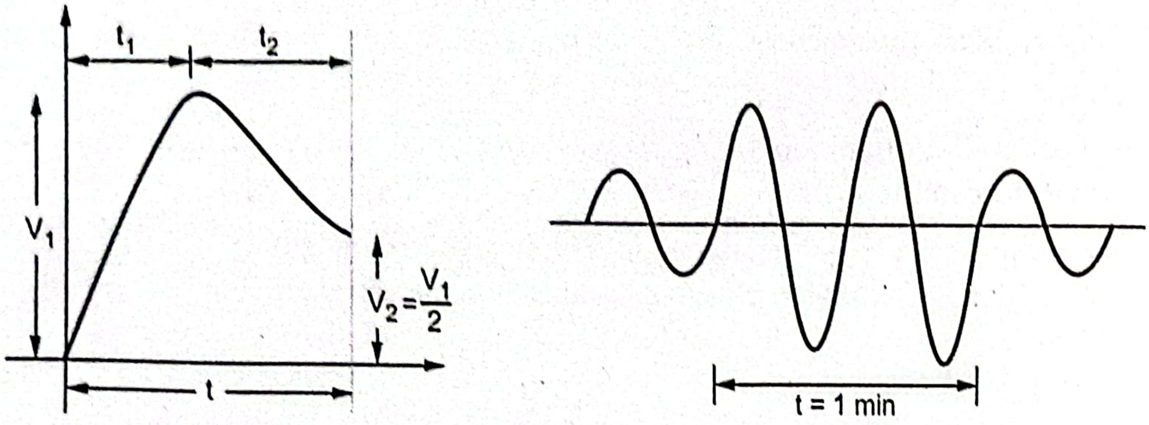

t < 100 µsec
V
Time (µsec)
t < 3000 µsec
V
Time (µsec)

(a) Lightning surge

(b) Switching surge

Fig. 1.12.2

4) The withstand levels of the equipment. Typical impulse test voltage wave is shown in the Fig. 1.12.3.



a) Impulse voltage wave
For lightning impulse test
t_1 = 1.2 μsec
t_2 = 50 μsec

b) Power frequency overvoltage test wave
For switching impulse test
t_1 = 250 μsec
t_2 = 2500 μsec

Fig. 1.12.3

1.12.1 Basic Impulse Insulation Level (BIL)

It is the reference level expressed in crest (peak) voltage value with standard 1.2/50 μsec lightning impulse wave. The electrical equipment under test must withstand test waves above BIL.

$$\text{Protective margin} = \begin{bmatrix}\text{Withstand level} \\ \text{of equipment}\end{bmatrix} - \begin{bmatrix}\text{Protective level} \\ \text{by surge arrester}\end{bmatrix}$$

It is required to have co-ordination between various equipments which are exposed to same voltage. It is also required to have co-ordination between different voltage levels in the network.

The time durations, rate of rise, highest values of overvoltages, lightning surges and switching surges in practice differ widely. Hence stresses on insulation due to these are also different. Power frequency overvoltages are having lower values (less overvoltage factor) but lasts for longer duration. The lightning and switching surges are having greater overvoltage factor but their durations are smaller. The different test waveforms are developed based on field survey carried out at various locations and used for testing equipment's withstand capability.

1.12.2 Insulation Co-ordination

The combination of rated voltage and specified one minute power frequency withstand level, lightning impulse withstand level, switching impulse withstand level for the electrical equipment together are called insulation level of the equipment.

The grading between the insulation level of the equipment, protective level of surge arrester and insulation levels of other equipment and surge arresters at the same voltage level, the grading between various voltage levels in the network is called insulation co-ordination. Following are the steps in insulation co-ordination

i) The insulation level of the equipment is determined.

ii) The protective level of surge arrester is decided.

iii) The co-ordination 1 and 2 for each equipment is done.

iv) The co-ordination 3 for different equipments at the voltage level is done.

v) The co-ordination 3 is executed at various voltage levels.

Review Questions

1. *What do you mean by insulation co-ordination ? Give the significance of basic insulation levels in insulation co-ordination.*
2. *Discuss the factors to be considered while deciding the insulation requirements.*
3. *Write a short note on insulation co-ordination.* **AU : May-13, 15, Marks 5**
4. *Enumerate the basic ideas of insulation coordination.* **AU : Dec.-13, 14, Marks 8**

1.13 Two Marks Questions with Answers

Q.1 Mention the various parameters used for discriminating fault location in a power system. **AU : Dec.-05**

Ans. : The various parameters are the magnitude, frequency, wave shape, phase angle, duration, direction and ratio of voltage or current from the P.T.s or C.T.s connected in the power system.

Q.2 What is switchgear ? **AU : May-07**

Ans. : The combination of devices used for switching, controlling, isolating and protecting the electrical circuits and equipments of an electrical power system is called switchgear. The switchgear includes the devices like circuit breakers, disconnecting switches, fuses, current and potential transformers, earthing switches, relays etc.

Q.3 State any four functions of protective relaying. **AU : Dec.-06, May-07, 13, 15**

OR Why protection scheme is needed for power system ? **AU : May-18**

Ans. : 1. To disconnect the abnormally operating part so as to avoid the damage within effective operation of the rest of the system.

2. To prevent the subsequent faults arising due to the primary fault.

3. To disconnect the faulty part as quickly as possible so as to minimise the damage to the faulty part itself.

4. To improve system performance, reliability and service continuity.

Q.4 What is protective zone ? **AU : May-11, 15, 19**

Ans. : A protective zone is a separate zone which is established around each element of a power system such that any fault occurring within that zone will cause the tripping of relays which causes opening of all the circuit breakers located in that zone so as to disconnect the faulty part as quickly as possible.

Q.5 What is dead spot or blind spot in a power system ? **AU : Dec.-16**

Ans. : Practically the protective zones are overlapped so that no area of power system remains unprotected. The area of a power system which remains unprotected such that any fault occurring in that area would not be cleared at all is called dead spot or blind spot of a power system.

Q.6 Define selectivity of protective relaying. **AU : Dec.-04**

Ans. : The selectivity is the ability of the protective system to identify the faulty part correctly and to disconnect that part without affecting the rest of the healthy part of the system.

Q.7 List the basic requirements or essential qualities of protective relaying.

AU : May-04, Dec.-06, 08

Ans. : The basic requirements of protective relaying are i) Reliability ii) Selectivity and discrimination iii) Speed and time iv) Sensitivity v) Stability vi) Adequateness vii) Simplicity and economy.

Q.8 Define burden and over-reach as related to protective relaying. **AU : May-04**

Ans. : Burden : It is the power absorbed by the relay elements expressed in volt-amperes for a.c. and in watts for d.c. circuits, under rated current and voltage conditions.

Over-reach : The operation of the relay beyond the set distance is called over-reach.

Q.9 What is the difference between primary and back up protection ?

AU : May-06, Dec.-12, 16

Ans. : The primary protection is the main protection which comes into action instantly when the fault occurs. The protection which comes into the play when the primary protection fails is called backup protection. When the primary protection is made inoperative for the maintenance purpose then backup protection acts like main protection.

Q.10 What is the meaning of burden on C.T. ? **AU : Dec.-06**

Ans. : The **burden on C.T.** is defined as the load connected across its secondary, which is usually expressed in Volt Amperes (VA). It can also be expressed in terms of impedance at the rated secondary current at a given power factor.

Q.11 Define pickup value and plug setting multiplier. **AU : May-07,22, Dec.-10,16**

Ans. : **Pickup value :** It is the minimum value of an actuating quantity at which relay starts operating. In most of the relays actuating quantity is current in the relay coil and pickup value of current is indicated along with the relay.

Plug setting multiplier (P.S.M.) : The ratio of actual fault current in the relay coil to the pickup current is called plug setting multiplier (P.S.M.) Mathematically it can be expressed as,

$$\text{P.S.M.} = \frac{\text{Fault current in relay coil}}{\text{Pickup value}} = \frac{\text{Fault current in relay coil}}{\text{\% current setting} \times \text{Rated secondary current of C.T.}}$$

Q.12 What is the need for protection zones ? **AU : May-08,22**

Ans. : A power system consists of various equipments of varied nature such as generators, transformers, bus bars, transmission lines etc. The protection need for each of these equipments is different. Hence the various protection zones are defined each covering one type of equipment.

Q.13 What is time setting multiplier (TSM) ? **AU : Dec.-10,16, May-22**

Ans. : A feature provided to a relay which controls its time of operation is called time setting multiplier. The value of time setting multiplier along with the time obtained from time/P.S.M. curve decides the actual time of operation of the relay.

Actual time of operation = Time in seconds × Time setting multiplier

Q.14 List the methods of backup protection.

Ans. : 1. Relay backup protection 2. Breaker backup protection

3. Remote backup protection 4. Centrally co-ordinated backup protection

Q.15 State the possible causes of failure of primary protection.

Ans. : 1. Failure in circuit breaker 2. Failure in protective relay

3. Failure in tripping circuit 4. Failure in d.c tripping voltage

5. Loss of supply to the relay.

Q.16 What are the possible effects if the faulty part is not disconnected for a long time ? **AU : Dec.-12**

Ans. : 1. The device carrying fault current may get damaged.

2. The failure leads to reduction in voltage.

3. The reduced voltage may affect the motors and other equipments adversely.

4. Subsequent other faults may get generated in the system.

Q.17 Why time lag is provided in the relay operation ?

Ans. : 1. To have clear discrimination between primary and backup protection.

2. To prevent unnecessary operation of relays under the conditions such as transients, starting inrush of current etc.

Q.18 What is fault clearing time ?

Ans. : **Fault clearing time :** The total time required between the instant of fault and the instant of final arc interruption in the circuit breaker is fault clearing time. It is sum of the relay time and circuit breaker time.

Q.19 Define sensitivity factor of a protective zone.

Ans. : Mathematically the sensitivity is expressed by a factor called sensitivity factor K_S. It is the ratio of minimum short circuit current in the protected zone to the minimum operating current required for the protection to start.

$$K_S = \frac{I_S}{I_o}$$

Where K_S = Sensitivity factor

I_S = Minimum short circuit current in the zone

I_o = Minimum operating current for the protection.

Q.20 Why the secondary of C.T. should not be open ? **AU : Dec.-11, 14, May-15**

Ans. : If the secondary of C.T. is kept open then current through secondary becomes zero hence the ampere turns produced by secondary which generally oppose primary ampere turns becomes zero. As there is no counter m.m.f., unopposed primary m.m.f. produce high flux in the core. This produces excessive core loss heating the core. It also produces heavy e.m.f. on primary and secondary side which may damage the insulation of the winding. This is dangerous from the operator point of view as well. Hence the secondary of C.T. should not be open.

Q.21 What is pickup current ? **AU : Dec.-14, May-13**

Ans. : The minimum value of the actuating current at which the relay starts operating is called pickup current of the relay.

Q.22 What are the different types of zones of protection ? **AU : Dec.-13**

Ans. : The different types of zones of protection are generator protection zone, low voltage switchgear protection zone, busbar protection zone, transformer protection zone, high voltage switchgear protection zone and transmission line protection zone.

Q.23 What is meant by autoreclosing ? **AU : Dec.-13**

Ans. : The faults on a power system are classified based on time as transient, semipermanent and permanent. About 80 % of the faults are transient which are momentary. The circuit breakers opening due to such faults have mechanism that can automatically close the circuit breaker. This is called autoreclosing.

Q.24 What is the function of isolating switch ? **AU : Dec.-13**

Ans. : A knife switch used to disconnect the part of a power system on no load condition so that the part should not carry any current is called an isolating switch. It is operated only when the load is switched off using the circuit breakers.

Q.25 What are the types of fuses ? **AU : Dec.-13**

Ans. :
1. Expulsion fuse
2. Rewirable or semi-enclosed fuse
3. Cartridge fuse
4. Drop-out fuse
5. Liquid fuse
6. Open fuse
7. Striker fuse
8. HRC fuse

Q.26 Define target.

Ans. : It is a device which is used to indicate the operation of the relay. It is also called flag.

Q.27 Define reach.

Ans. : The limiting set distance in which protective system responds to the faults is called reach of the protective system.

Q.28 What is unit protection and nonunit protection system ?

Ans. : A protective system in which the protection zone is clearly defined by the C.T. boundaries is called unit protection system. The faults occurring in its defined protected zone are isolated. A nonunit protection system is the one which is activated even for the faults which are external to its protected zone.

Q.29 What is primary protection ? **AU : Dec.-17**

Ans. : The protection in which the fault occurring in a line is cleared by its own relay and circuit breaker is called primary protection. It is the first line of defence. It comes into action instantly when the fault occurs.

Q.30 What is meant by relay operating time ? **AU : Dec.-12**

Ans. : The time elapses from the moment when the actuating quantity attains a value equal to the pickup value of the relay until the relay operates its contacts is called the relay operating time.

Q.31 What are the different types of faults in power system ?

AU : Dec.-07, 17, May-12, 14, 17

Ans. :

1. **Symmetrical faults :** The fault which gives rise to equal fault currents in all the lines with displacement of 120° between them. The example is line to line to line fault i.e. shorting of all three lines.
2. **Unsymmetrical faults :** The fault which gives rise to unequal fault currents in all the lines with unequal displacements between them. The examples are line to ground, line to line, line to line to ground faults.

Q.32 What are the causes of faults in a power system ? **AU : May-11, Dec.-13**

Ans. : The various causes of faults in a power system are failure of insulation of conductor at one or more places, conducting object comes in contact with the live part of the system, mechanical failure, excessive internal and external stresses, over voltages due to switching surges, lightning strokes, heavy winds and storms, falling of trees on the lines, accidents of vehicles with the towers or poles, perching of birds on the lines, accidental short circuits due to snakes, kites, strings etc.

Q.33 What are the duties of fault limiting reactors ? **AU : Dec.-13**

Ans. :

1. To localise the fault at a point where it originates and limiting the fault current to flow to other healthy part of the system.
2. To protect the equipments from overheating by limiting the short circuit current.
3. To protect the devices from failure by limiting short circuit forces.
4. To permit the use of circuit breakers of lower rating hence reducing the cost.

Q.34 State the various types of unsymmetrical faults. **AU : Dec.-22**

Ans. :

1. Single line to ground fault which involves the connection of one of the lines to ground.
2. Line to line fault in which two lines are in connection with each other.
3. Double line to ground fault in which two lines are in contact with each other and connected to the ground.

Q.35 Mention the significance of neutral grounding.

Ans. : The earthing or grounding is nothing but the connection of neutral point of the supply system to the general mass of the earth in such a way that immediate discharge of electricity can take place without danger. It ensures safety of personnel or human beings against electrical shocks (including animals and plants) and equipments. It also avoids accidents which otherwise may take place. The equipment is also protected against lightning and voltage surges. The voltage stress on the lines is also reduced along with that on the equipment with respect to earth under abnormal conditions.

Q.36 What are objectives of earthing ?

Ans. : Following are the objectives of earthing :

i) It should provide adequate safety of operating personnel/human being (including animals and plants) against electrical shocks/hazards and avoid accidents.

ii) It should provide an alternative path for the fault current to flow so as to reduce danger of the user.

iii) It should ensure that all the exposed conductive parts do not reach a dangerously high potential and should reduce the stress on the lines along with that on the equipment with respect to earth under abnormal conditions.

iv) It should be able to maintain the voltage at any part of an electrical system at a known value so as to avoid excessive voltage on the appliances or equipment or over current situation.

Q.37 What are various methods of earthing in substations ? **AU : May-15**

Ans. : The earthing in substations is carried out with the help of equipments such as electrodes, driven rods, risers and grounding grid or mat consisting of number of meshes and connected to several earth electrodes driven at intervals. The various methods adopted for earthing are :

i) Solid or effective grounding ii) Resistance grounding

iii) Reactance grounding iv) Resonant grounding

Q.38 What are advantages of neutral grounding ?

Ans. : Following are advantages of neutral grounding :

i) The faulty part can be isolated from the remaining system with the help of earth fault relays.

ii) The transient voltage in the system with grounded neutral is small.

iii) The arcing grounds are prevented from occurring by using suitable switchgears.

iv) The voltage of healthy phases during faulty condition remains nearly constant as the neutral point is not shifted.

v) The static charges which gets induced are grounded immediately. This avoids disturbance in the system.

vi) Reliability of the system is improved.

vii) The discriminative type of fault indicator can be installed on such systems.

Q.39 What is need of an earthing system ?

OR

What is need for power system earthing ? **AU : Dec.-10**

Ans. : In order to provide safety of personnel or human beings against electrical shocks (including animals and plants), to reduce the possibility of getting electrical shocks and avoiding accidents, to protect the equipments, buildings, machinery/appliances against lightning and voltage surges, to reduce stress on the lines along with that on the equipment with respect to earth under abnormal conditions earthing is required.

Q.40 What do you mean by earthing ?

Ans. : The earthing or grounding is nothing but the connection of neutral point of the supply system or the star point of any electrical equipment like generator or transformer to the general mass of the earth in such a way that immediate discharge of electricity can take place without danger so as to ensure the safety.

Q.41 What do you mean by coefficient of earthing ?

Ans. : The ratio, expressed as a percentage, of the highest root-mean-square (rms) line-to-ground power-frequency voltage (E_{LG}) on a sound phase, at a selected location, during a fault to ground affecting one or more phases to the line-to-line power-frequency voltage (E_{LL}) that would be obtained at the selected location with the fault removed.

$$\therefore \quad \text{Coefficient of earthing} = \frac{E_{LG}}{E_{LL}} \times 100$$

Q.42 Define earth resistance.

Ans. : The resistance of earthing electrode to the real earth is known as earth resistance which is expressed in Ohms.

$$\text{Earth resistance} = \frac{\text{Voltage across earth electrode}}{\text{Current in the earth electrode}}$$

Q.43 State the disadvantages of ungrounded neutral.

Ans. : Following are the disadvantages of ungrounded neutral :

i) Under faulty condition, large transient voltages with magnitude several times that of normal value is produced causing the breakdown of insulation resulting in damage of the concerned equipment.

ii) System cannot be protected from earth fault and arcing ground may occur.

iii) There is no path to earth for voltages due to lightning surges.

Q.44 State the expression for resistance of driven rods with uniform current dissipation method.

Ans. : The earthing resistance of driven rod with length l and diameter d is given by,

$$R = \frac{\rho}{2\pi l}\left(\ln\frac{8l}{d}-1\right)$$

Q.45 Define screening coefficient.

Ans. : The screening coefficient for n electrodes in parallel is defined as,

$$R = \frac{\text{Resistance of one electrode}}{(\text{Resistance of n electrodes in parallel})\times n}$$

Q.46 Give atleast two merits of a resistance grounded system.

Ans. : The advantages of resistance grounding are as follows :

1. The discriminative type of switchgears may be used for protection.
2. The hazards due to arcing grounds are minimized.
3. The influence on neighbouring communication circuits is minimized due to lower value of fault current flowing through earth as compared to that in case of solidly grounded system.

Q.47 Define the term "Insulation Coordination".

Ans. : The grading between the insulation level of the equipment, protective level of surge arrester and insulation levels of other equipment and surge arresters at the same voltage level, the grading between various voltage levels in the network is called insulation co-ordination.

Q.48 How is arcing ground avoided ?

Ans. : Arcing ground is avoided with the use of Peterson coil or arc suppression coil connected between neutral and earth along with suitable switchgears.

Q.49 Why earth wire is provided in overhead transmission lines ? **AU : Dec.-15**

Ans. : The earth wire is provided in overhead transmission lines because,

i) To protect the line conductors from direct lightning strokes.

ii) To reduce the line outages.

iii) To reduce the interference on neighbouring installations.

iv) To transmit telecommunication signals.

Q.50 What is the difference between a short circuit and an overload ? **AU : Dec.-15**

Ans. : When there is short circuit, the impedance at the fault point is almost zero and the voltage at the fault point is zero. The short circuit current is very high. While an overload means the load is higher than the rated load which is specified as the safe load. Thus the current is also higher than the safe load. Thus the current is also higher than the safe designed rated value. The overload does not cause damage instantly but if persists for long time, can cause damage to the system.

Q.51 Give the difference between circuit breaker and switch. **AU : May-17**

Ans. : A circuit breaker is an electrical switch which is capable of detecting abnormal conditions and capable of making and breaking currents under normal as well as abnormal conditions like short circuit. A switch can not carry the breaking currents under abnormal conditions like short circuit.

Q.52 What are the effects of short circuit faults on power system, if the fault remain uncleared ? **AU : Dec. - 18, May-19**

Ans. : 1. Heavy short circuit current flows due to short circuit fault which can damage the power system equipments.

2. It produces overheating and excessive mechanical stresses.
3. It can cause fire due to arcing caused by heavy currents. The fire can spread to other healthy parts as well, if fault remain uncleared.
4. The overheating causes weakening of insulation of the conductors.
5. The generators can loose synchronism causing total shutdown of the system.
6. It reduces the overall reliability of the power system.

Q.53 Define positive sequence component and zero sequence component **AU : Dec.-22**

Ans. : The component in a balanced system with the same phase sequence as the original supply sequence is called positive sequence component.

The component in an unbalanced system which flows through the neutral which are equal in magnitude and phase is called zero sequence component.

The component in an unbalanced system with the opposite phase sequence as the original supply sequence is called negative sequence component.

Q.54 What is Peterson coil grounding ? **AU : May-22**

Ans. : Peterson coil is iron cored reactor between neutral of system and earth. Its function is to make arcing earth faults self extinguishing and in the case of sustained faults to reduce the earth current to low value so that system can supply power with one line earthed. It works on the principle that when inductance and capacitance are connected in parallel, resonance takes place due to which the fault current is reduced or can be neutralized.

1.14 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *Explain the detail about the need and different types of earthing scheme.* **[Sections 1.10 and 1.11]** **[10]**

Q.2 *Explain the essential qualities of protection and explain them in detail.* **[Section 1.7]** **[6]**

May-17

Q.3 *Discuss in detail about different protection schemes.* **[Section 1.6]** **[16]**

Q.4 *Explain Arc suppression coil earthing with neat diagram.* **[Section 1.11.4]** **[16]**

Dec.-17

Q.5 *Explain the various methods of neutral grounding.* **[Section 1.11]** **[16]**

Q.6 *What are the essential qualities of protective relay ? Explain in detail.* **[Section 1.7]** **[16]**

May-18

Q.7 *Explain clearly about the zones of protection in power system.* **[Section 1.5]** **[8]**

Q.8 *Briefly discuss about nature and causes of faults.* **[Section 1.4]** **[8]**

Q.9 *Explain in detail about the need and different methods for neutral grounding with suitable diagram.* **[Sections 1.10 and 1.11]** **[16]**

Dec.-18

Q.10 *What are the essential requirements of protective relaying ? Justify.* **[Section 1.7]** **[7]**

Q.11 *Discuss briefly about primary protection and back-up protection.* **[Section 1.6]** **[6]**

Q.12 *Discuss the following neutral grounding schemes. Illustrate your answers with appropriate phasor diagrams, benefits and recommendations.*

i) Resistance earthing **[Section 1.11.2]** **[5]**

ii) Reactance earthing **[Section 1.11.3]** **[3]**

iii) Arc suppression coil **[Section 1.11.4]** **[5]**

May-19

Q.13 *Describe the different faults occurring in power system. Which of these are more frequent ?* **[Section 1.4]** **[5]**

Q.14 *Formulate an expression for the reactance of the Peterson coil in terms of capacitance of the protected line.* **[Section 1.11.4]** **[5]**

Q.15 *Explain the overlapping of protective zones with neat sketch.* **[Section 1.5]** **[5]**

Q.16 *Describe the essential qualities of a protective relay.* **[Section 1.7]** **[5]**

(Regulation 2017)

May-22

Q.17 *Explain the concept of back up relay and the methods of back-up protection.* **[Refer section 1.6]** **[13]**

Q.18 *Briefly explain the methods of neutral grounding and discuss its advantages.* **[Refer section 1.11]** **[13]**

Dec.-22

Q.19 *Discuss the nature and causes of faults in a power system.* **[Section 1.4]** **[13]**

Q.20 *Explain the method of resistance and reactance grounding of the power system with neat sketch* **[Sections 1.11.2 and 1.11.3]**

❑❑❑

UNIT II

2

Basics of Relays

Syllabus

Operating principles of relays - Universal torque equation - R-X diagram - Electromagnetic relays - Overcurrent, Directional and non-directional, Distance, Differential, Negative sequence and under frequency relays.

Contents

2.1 *Introduction*
2.2 *Classification of Protective Relays*
2.3 *Electromagnetic Attraction Relays* .... **May-08,17, Dec.-13,17,22,** · · *Marks 8*
2.4 *Induction Type Relays* .... **May-11,** · · · · · · · · · · · · · · · · *Marks 8*
2.5 *Universal Relay Torque Equation* .... **May-13,** · · · · · · · · · · · · · · · · *Marks 4*
2.6 *Introduction to Overcurrent Relays* .... **May-12, Dec.-14,18,** · · · · · · *Marks 6*
2.7 *Nondirectional Induction Type Overcurrent Relay* .... **Dec.04,06,07,10,17,18,22,** .... **May-05,** · · · · · · · · · · · · · · · *Marks 12*
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2.13 *Mho Relay or Admittance Relay* .... **May-06,12,13,22,** .... **Dec.-07,11,12,13,15,16,** · · · *Marks 6*
2.14 *Classification of Distance Relays*
2.15 *Setting of Distance Relays* .... **May-06, Dec.-12,** · · · · · · · · *Marks 6*
2.16 *Differential Relays* .... **Dec.-05,06,08, May-12,18,** · *Marks 16*
2.17 *Frequency Relay* .... **Dec.-10,14, May-14,** · · · · · · *Marks 8*
2.18 *Negative Sequence Relays* **May-06,14,15,18,19, Dec.-13,***Marks 8*
2.19 *Thermal Relays*
2.20 *Two Marks Questions with Answers*
2.21 *University Questions with Answers (Long Answered Questions)*

2.1 Introduction

An important element of any protective relaying scheme is a relay. It is a device which detects the fault and is responsible to energize the trip circuit of a circuit breaker. This isolates the faulty part from rest of the system. In an electromagnetic relay, the driving torque is created based on an electrical or electronic principle. While the restraining torque is generally provided with the help of springs. The two torques are mechanically compared and the relay operates when driving or operating torque is more than the restraining torque. Thus,

T_d = Driving torque or operating torque

T_r = Restraining torque

T_R = Resultant torque = $T_d - T_r$

The relay operates when the resultant torque T_R is positive. Let us study the basic action of a trip circuit with a relay.

2.1.1 Basic Trip Circuit Operation

Consider a simplified circuit of a typical relay as shown in the Fig. 2.1.1. Usually the relay circuit is a three phase circuit and the contact circuit of relays is very much complicated. The Fig. 2.1.1 shows a single phase simplified circuit to explain the basic action of a relay. Let part A is the circuit to be protected. The current transformer C.T. is connected with its primary in series with the line to be protected. The secondary of C.T. is connected in series with the relay coil. The relay contacts are the part of a trip circuit of a circuit breaker. The trip circuit consists of a trip coil and a battery, in addition to relay contacts. The trip circuit can operate on a.c. or d.c.

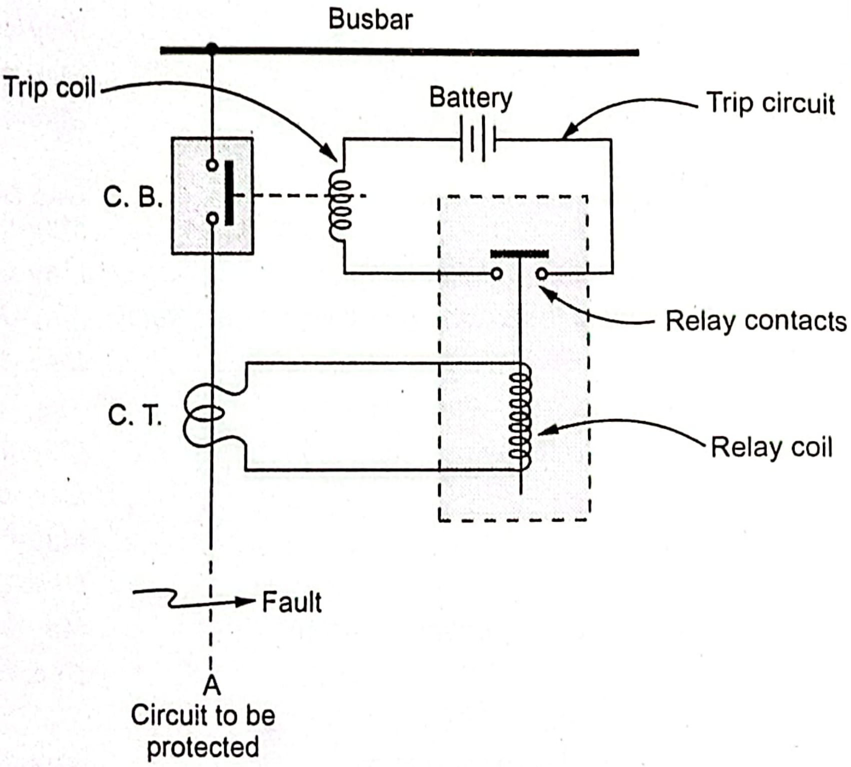


Fig. 2.1.1 Typical relay circuit

If the fault occurs as shown in the Fig. 2.1.1, then current through the line connected to A increases to a very high value. The current transformer senses this current.

Accordingly its secondary current increases which is nothing but the current through a relay coil. Thus the relay contacts get closed mechanically under the influence of such a high fault current. Thus the trip circuit of a circuit breaker gets closed and current starts flowing from battery, through trip coil, in a trip circuit. Thus the trip coil of a circuit breaker gets energised. This activates the circuit breaker opening mechanism, making the circuit breaker open. This isolates the faulty part from rest of the healthy system.

2.1.2 Auxiliary Switch

Another important device in the trip circuit is an auxiliary switch. It is a multipoint switch generally 4 point, 6 point, 12 point or 24 point. This switch is mechanically coupled with operating mechanism of the circuit breaker. Thus when circuit breaker opens, the switch also gets opened. The switch is in the trip circuit and hence when it opens, it breaks the current through the trip circuit. Once the current in the trip circuit is interrupted the relay contacts come to normal position. The advantage of an auxiliary switch is that the breaking of trip circuit takes place only across the switch and hence possible arcing due to current interruption across the relay contacts gets avoided. Such arcing is harmful for relay contacts as relay contacts are delicate and light. To interrupt a current through the inductive circuit like trip circuit a robust mechanical switch is necessary. This purpose is served by an auxiliary switch, protecting delicate relay contacts. In addition to this, indication circuits showing whether circuit breaker is open or close and some other control circuits also get connected or disconnected by an auxiliary switch.

The auxiliary switch is generally placed in the control cabinet of the circuit breaker.

Thus a relay cannot prevent a fault but it identifies the location of fault and prevents the adverse effects of the fault on the power system. Hence a relay is said to be the brain of a protective system which minimizes the effects of faults and minimizes the damage due to the faults. It also provides the information about the location and type of fault and this information assists in fast repairing of the fault.

Review Question

1. *Draw a trip circuit including CT, relay, battery, circuit breaker and explain its operation.*

2.2 Classification of Protective Relays

All the relays consist of one or more elements which get energised and actuated by the electrical quantities of the circuit. Most of the relays used now a days are electro-mechanical type which work on the principles of electromagnetic attraction and electromagnetic induction.

2.2.1 Electromagnetic Attraction Type Relays

The electromagnetic attraction type relays operate on the principle of attraction of an armature by the magnetic force produced by undesirable current or movement of plunger in a solenoid. These relays can be actuated by a.c. or d.c. quantities. The various types of these relays are,

1. **Solenoid type :** In this relay, the plunger or iron core moves into a solenoid and the operation of the relay depends on the movement of the plunger.
2. **Attracted armature type :** This relay operates on the current setting. When current in the circuit exceeds beyond the limit, the armature gets attracted by the magnetic force produced by the undesirable current. The current rating of the circuit in which relay is connected plays an important role in the operation of the relay.
3. **Balanced beam type :** In this relay, the armature is fastened to a balanced beam. For normal current, the beam remains horizontal but when current exceeds, the armature gets attracted and beam gets tilted causing the required operation.

2.2.2 Induction Type Relays

These relays work on the principle of an electromagnetic induction. The use of these relays is limited to a.c. quantities. The various types of these relays are,

1. **Induction disc type :** In this relay, a metal disc is allowed to rotate between the two electromagnets. The electromagnets are energised by alternating currents. The two types of constructions used for this type are shaded pole type and watthour meter type.
2. **Induction cup type :** In this relay, electromagnets act as a stator and energised by relay coils. The rotor is metallic cylindrical cup type.

2.2.3 Directional Type Relays

These relays work on the direction of current or power flow in the circuit. The various types of these relays are,

1. **Reverse current type :** The relay is actuated when the direction of the current is reversed or the phase of the current becomes more than the predetermined value.
2. **Reverse power type :** The relay is actuated when the phase displacement between applied voltage and current attains a specified value.

2.2.4 Relays Based on Timing

In relays the time between instant of relay operation and instant at which tripping of contacts takes place, can be controlled. This time is called operation time. Based on this, the time relays are classified as,

1. **Instantaneous type :** In this type no time is lost between operation of relay and tripping of contacts. No intentional time delay is provided.
2. **Definite time lag type :** In this type intentionally a definite time lag is provided between operation of relay and tripping of contact.
3. **Inverse time lag type :** In this type, the operating time is approximately inversely proportional to the magnitude of the actuating quantity.

2.2.5 Distance Type Relays

These relays work on the principle of measurement of voltage to current ratio. In this type, there are two coils. One coil is energised by current while other by voltage. The torque produced is proportional to the ratio of the two quantities. When the ratio reduces below a set value, the relay operates. The various types of these relays are,

1. **Impedance type :** In this type, the ratio of voltage to current is nothing but an impedance which is proportional to the distance of the relay form the fault point.
2. **Reactance type :** The operating time is proportional to the reactance which is proportional to the distance of the relay from the fault point.
3. **Admittance type :** This is also called mho type. In this type, the operating time is proportional to the admittance.

2.2.6 Differential Type Relays

A differential relay operates when the vector difference of two or more electrical quantities in the circuit in which relay is connected, exceeds a set value. These are classified as,

1. **Current differential type :** In this type, the relay compares the current entering a section of the system and the current leaving the section. Under fault condition, these currents are different.
2. **Voltage differential type :** In this type, two transformers are used. The secondaries of the transformers are connected in series with the relay in such a way that the induced e.m.f.s are in opposition under normal conditions. Under fault condition, primaries carry different currents due to which induced e.m.f.s no longer remain in opposition and the relay operates.

2.2.7 Other Types of Relays

Various other types of relays which are used in practice are,

1. **Under voltage, current, Power relay :** This relay operates when the voltage, current or power in a circuit falls below a set value.
2. **Over voltage, current, Power relay :** This relay actuates when the voltage, current or power in a circuit rises above a set value.
3. **Thermal relay :** This relay actuates due to the heat produced by the current in the relay coil.
4. **Rectifier relay :** In this relay, the quantities to be sensed are rectified and then given to the moving coil unit of the relay.
5. **Permanent magnet moving coil relay :** In this relay, the coil carrying current is free to rotate in the magnetic field of a permanent magnet. This is used for d.c. only.
6. **Static relay :** This relay uses some electronic method for sensing the actuating quantity. It uses a stationary circuit.
7. **Gas operated relay :** The gas pressure is adjusted according to the variations in the actuating quantity. This gas pressure is used to actuate the relay. Buchholz relay is an example of such type of relay.

Review Question

1. *Discuss the classification of protective relays.*

2.3 Electromagnetic Attraction Relays

AU : May-08,17, Dec.-13,17,22

In these relays, there is a coil which enerzises an electromagnet. When the operating current becomes large, the magnetic field produced by an electromagnet is so high that it attracts the armature or plunger, making contact with the trip circuit contacts. These are simplest type of relays. The various types of electromagnetic attraction type relays are,

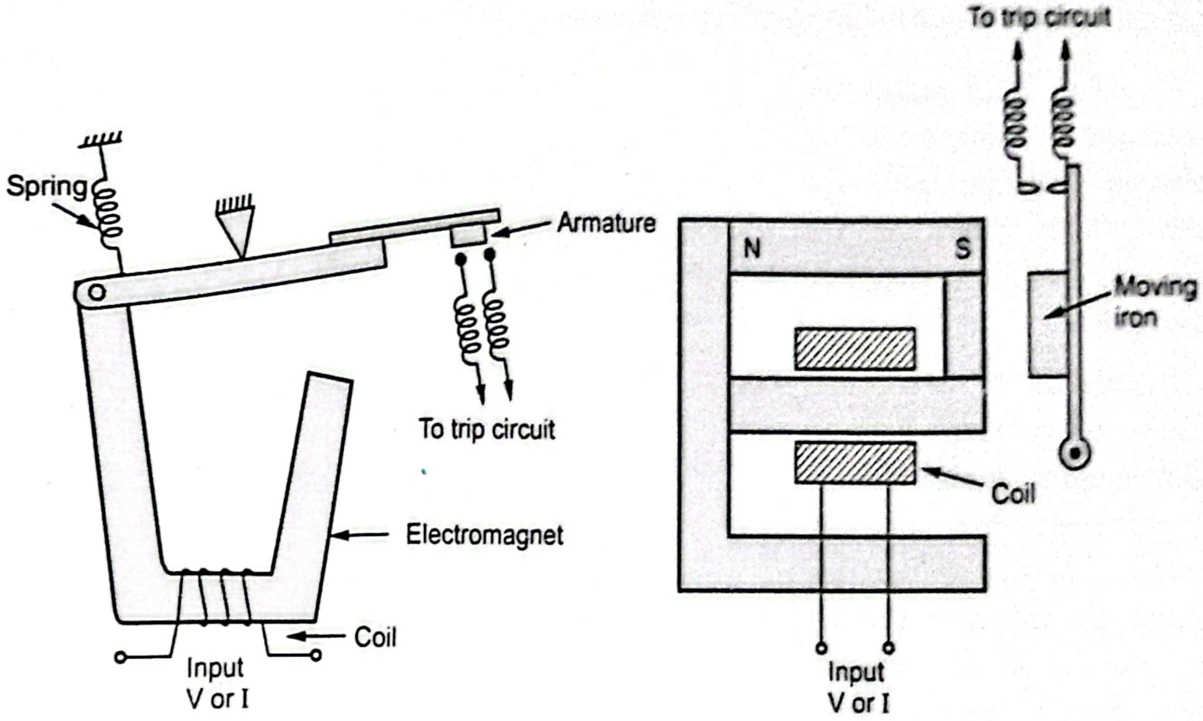
1. Attracted armature relay 2. Solenoid and plunger type relay

2.3.1 Attracted Armature Type Relay

There are two types of structures available for attracted armature type relay which are,

i) Hinged armature type ii) Polarised moving iron type

The two types of attracted armature type relays are shown in the Fig. 2.3.1 (a) and (b).



(a) Hinged armature type relay (b) Polarised moving iron type relay

Fig. 2.3.1

In attracted armature type, there exists a laminated electromagnet which carries a coil. The coil is energized by the operating quantity which is proportional to the circuit voltage or current. The armature or a moving iron is subjected to the magnetic force produced by the operating quantity. The force produced is proportional to the square of current hence these relays can be used for a.c. as well as d.c. The spring is used to produce restraining force. When the current through coil increases beyond the limit under fault conditions, armature gets attracted. Due to this it makes contact with contacts of a trip circuit, which results in an opening of a circuit breaker.

The minimum current at which the armature gets attracted to close the trip circuit is called **pickup current**.

Generally the number of tappings are provided on the relay coil with which its turns can be selected as per the requirement. This is used to adjust the set value of an operating quantity at which relay should operate.

An important advantage of such relays is their high operating speed. In modern relays an operating time as small as 0.5 msec is possible. The current-time characteristics of such relays is hyperbolic, as shown in the Fig. 2.3.2.

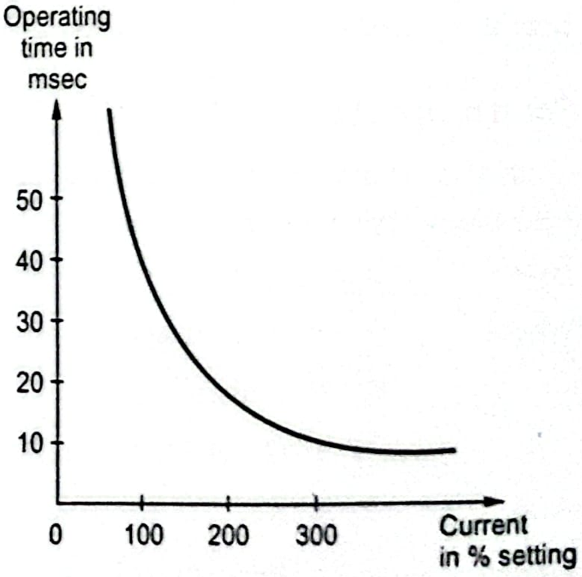


Fig. 2.3.2 Current-Time characteristics

2.3.2 Solenoid and Plunger Type Relay

The Fig. 2.3.3 shows the schematic arrangement of solenoid and plunger type relay which works on the principle of electromagnetic attraction.

It consists of a solenoid which is nothing but an electromagnet. It also consists a movable iron plunger. Under normal working conditions, the spring holds the plunger in the position such that it cannot make contact with trip circuit contacts.

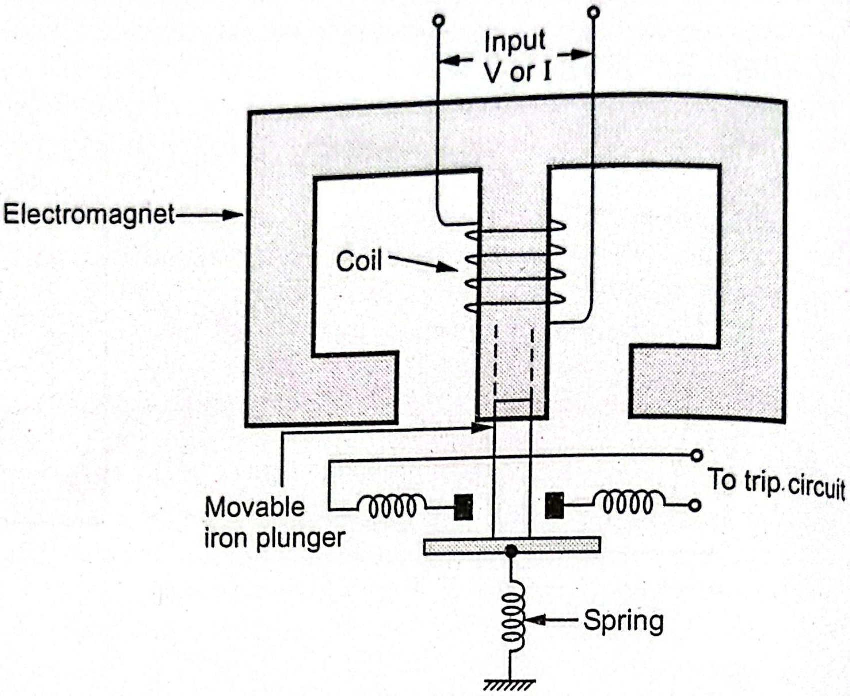


Fig. 2.3.3 Solenoid and plunger type relay

Under fault conditions when current through relay coil increases, the solenoid draws the plunger upwards. Due to this, it makes contact with the trip circuit contacts, which results in an opening of a circuit breaker.

2.3.3 Operating Principle of Electromagnetic Attraction Relays

The electromagnetic force produced due to operating quantity which is exerted on armature, moving iron or plunger is proportional to the square of the flux in the air gap. Thus neglecting the saturation effect, the force is proportional to the square of the operating current. Hence such relays are useful for a.c. and d.c. both.

For d.c. operation :

In d.c. operation, the electromagnetic force is constant. When this force exceeds the restraining force, the relay operates.

Now $F_e = K_1 I^2$

where F_e = Electromagnetic force

K_1 = Constant

I = Operating current in a coil

And $F_r = K_2$

where F_r = Restraining force due to spring including friction

K_2 = Constant

On the verge of relay operating, electromagnetic force is just equal to the restraining force.

$$\therefore \quad K_1 I^2 = K_2$$

$$\therefore \quad I^2 = \frac{K_2}{K_1}$$

$$\therefore \quad \boxed{I = \sqrt{\frac{K_2}{K_1}} = \text{Constant}}$$

This is the current at which relay operates in case of d.c. operation.

For a.c. operation : In a.c. electromagnetic relays, the electromagnetic force is proportional to square of the current but it is not constant. It is given by,

$$F_e = K I^2 = \frac{1}{2} K I_m^2 - \frac{1}{2} K I_m^2 \cos 2\omega t$$

where I_m = Maximum value of the operating current

K = Constant

It shows that the electromagnetic force consists of two components,

i) Constant, independent of time.

ii) Pulsating at double the frequency of applied voltage.

The total force thus pulsates at double the frequency.

If the restraining force F_r which is produced by the spring is constant then the armature of relay will be picked up at time t_1 and it drops off at time t_2 as shown in the Fig. 2.3.4.

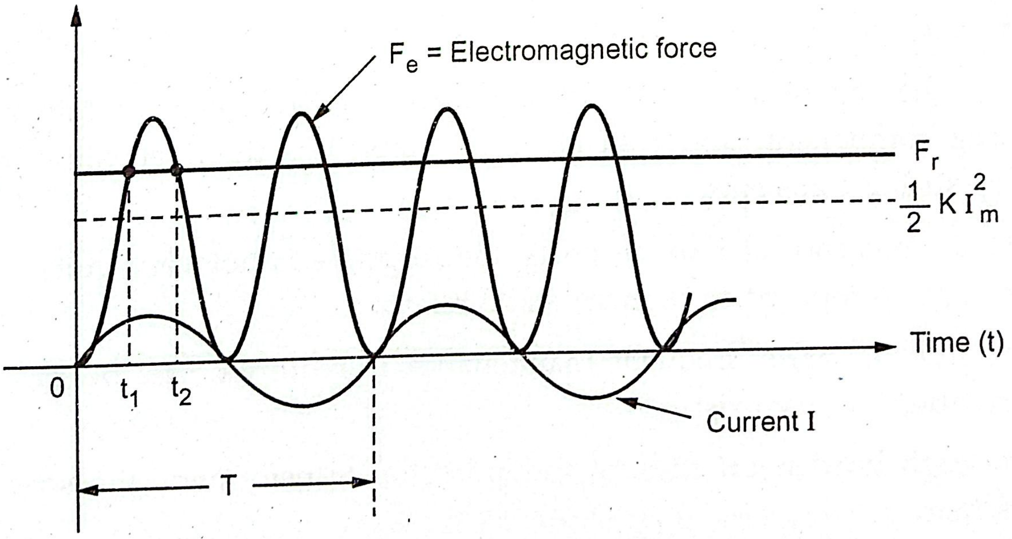


Fig. 2.3.4 Electromagnetic force and current curves

Thus relay armature pulsates at double frequency. This causes the relay to hum and produces a noise. It may cause damage to the relay contacts.

To overcome this difficulty, the air gap flux producing an electromagnetic force is divided into two fluxes acting simultaneously but differing in time phase. This causes resulting electromagnetic force to be always positive. If this is always greater than restraining force F_r then armature will not vibrate. The phase lag between the two components of flux can be easily produced using shading in a relay. The flux through the shaded pole lags behind the flux through the unshaded part.

2.3.4 Advantages of Electromagnetic Relays

The various advantages of electromagnetic relays are,

1. Can be used for both a.c. and d.c.
2. They have fast operation and fast reset.
3. These are almost instantaneous. Though instantaneous, the operating time varies with current. With extra arrangements like dashpot, copper ring etc. low operating and resetting times can be obtained.
4. High operating speed with operating time in few milliseconds also can be achieved.
5. The pickup can be as high as 90 - 95 % for d.c. operation and 60 to 90 % for the d.c. operation.
6. Modern relays are compact, simple, reliable and robust.

2.3.5 Disadvantages of Electromagnetic Relays

The few disadvantages of these relays are,

1. The directional feature is absent.
2. The working can be affected by the transients. As transients contain d.c. as well as pulsating component, under steady state value less than set value, the relay can operate during transients.
3. Due to the presence of moving parts, the response is not very quick due to inertia of the parts, compared to modern static relays.
4. Due to moving parts, frequent maintenance is required. The bearing friction and contact troubles may exist.
5. Due to high burden on current and potential transformers, the size is large and cost is more.
6. Due to the mechanical moving parts, the life is less and high failure rate compared to static relays.

2.3.6 Applications of Electromagnetic Relays

The various applications of these relays are,

1. The protection of various a.c. and d.c. equipments.
2. The over/under current and over/under voltage protection of various a.c. and d.c. equipments.
3. In the definite time lag over current and earth fault protection along with definite time lag over current relay.
4. For the differential protection.
5. Used as auxiliary relays in the contact systems of protective relaying schemes.

Review Questions

1. *Describe the operating principle of attracted armature type relay.* **AU : May-08, Marks 6**
2. *With neat diagram explain the construction and operating principle of electromagnetic relay.* **AU : Dec.-13, 17, May-17, Marks 8**
3. *State the advantages, disadvantages and applications of electromagnetic relays.*
4. *Discuss in detail about various types of electromagnetic relays.* **AU : Dec.-22, Marks 13**

2.4 Induction Type Relays

AU : May-11

The induction type relays are also called magnitude relays. These relays work on the principle of the induction motor or an energy meter. In these relays a metallic disc is allowed to rotate between the two electromagnets. The coils of the electromagnets are energized with the help of alternating currents. The torque is produced in these relays due to the interaction of one alternating flux with eddy currents induced in the rotor by another alternating flux. The two fluxes have same frequency but are displaced in time and space. As the interaction of alternating fluxes is the base of operation of these relays, these are not used for the d.c. quantities. These are widely used for protective relaying involving only a.c. quantities.

Based on the construction, the various types of the induction type relays are,

1. Shaded pole type
2. Watt hour meter type
3. Induction cup type

Before studying these types in detail, let us derive the torque equation for the induction type relays, which is same for all the three types of relays.

2.4.1 Torque Equation for Induction Type Relays

As mentioned earlier, the alternating currents supplied to two electromagnets produce the two alternating fluxes ϕ_1 and ϕ_2. These two fluxes have same frequency but they have a phase difference of α in between them such that ϕ_2 leads ϕ_1. Thus the two fluxes can be mathematically expressed as,

$$\phi_1 = \phi_{1m} \sin \omega t \quad \text{... (2.4.1)}$$

$$\phi_2 = \phi_{2m} \sin (\omega t + \alpha) \quad \text{... (2.4.2)}$$

These alternating fluxes cause the induced e.m.f.s in the rotor. Due to the induced e.m.f.s, the eddy currents i_1 and i_2 are circulated in the disc. The two eddy currents react with each other to produce a force which acts on the rotor.

The Fig. 2.4.1 shows how the forces are produced in a section of rotor due to the alternating fluxes. The instant considered to show the various quantities is when both the fluxes are directed downwards and are increasing in magnitude. The induced eddy currents lag behind the respective fluxes by 90 °.

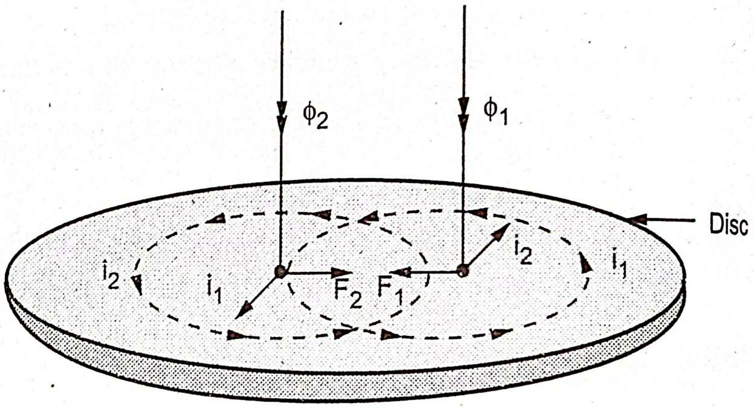


Fig. 2.4.1 Torque production

Assumption : The parts of rotor in which rotor currents flow have negligible self inductance and hence the rotor currents are in phase with the respective induced voltages.

The induced voltages are proportional to the rate of change of fluxes and hence the eddy currents also are proportional to the rate of change of fluxes. Hence we can write,

$$i_1 \propto \frac{d\phi_1}{dt} \quad \text{... (2.4.3)}$$

$$i_2 \propto \frac{d\phi_2}{dt} \quad \text{... (2.4.4)}$$

Substituting ϕ_1 and ϕ_2 from (2.4.1) and (2.4.2) we get,

$$i_1 \propto \frac{d(\phi_{1m} \sin \omega t)}{dt} \propto \phi_{1m} \cos \omega t \quad \text{... (2.4.5)}$$

$$i_2 \propto \frac{d\,[\phi_{2m} \sin(\omega t + \alpha)]}{dt} \propto \phi_{2m} \cos (\omega t + \alpha) \quad \text{... (2.4.6)}$$

The forces are produced due to the interaction of ϕ_1 with i_2 and ϕ_2 with i_1.

$$\therefore \quad F_1 \propto \phi_1 i_2 \qquad \ldots (2.4.7)$$

and $$F_2 \propto \phi_2 i_1 \qquad \ldots (2.4.8)$$

The directions of F_1 and F_2 can be obtained by Flemings left hand rule. It can be seen from the Fig. 2.4.1 that the two forces are acting in the opposite directions and hence the net force acting on the disc is proportional to the difference between the two forces.

$$\therefore \quad F \propto F_2 - F_1$$

$$\therefore \quad F \propto \phi_2 i_1 - \phi_1 i_2 \qquad \ldots (2.4.9)$$

Substituting the proportional expressions of ϕ_1, ϕ_2, i_1, i_2 from (2.4.1), (2.4.2), (2.4.5) and (2.4.6) in the equation (2.4.9) we get,

$$\therefore \quad F \propto [\phi_{2m} \sin(\omega t + \alpha)\, \phi_{1m} \cos \omega t - \phi_{1m} \sin \omega t\, \phi_{2m} \cos(\omega t + \alpha)]$$

$$\propto \phi_{1m}\, \phi_{2m}\, [\sin(\omega t + \alpha) \cos(\omega t) - \sin(\omega t) \cos(\omega t + \alpha)]$$

$$\propto \phi_{1m}\, \phi_{2m}\, [\sin(\omega t + \alpha - \omega t)]$$

$$\therefore \quad F \propto \phi_{1m}\, \phi_{2m}\, \sin \alpha \qquad \ldots (2.4.10)$$

The equation (2.4.10) gives the net force acting on the disc which is proportional to $\sin \alpha$.

Substituting the r.m.s. values of the fluxes instead of maximum values we get,

$$\boxed{F \propto \phi_1\, \phi_2\, \sin \alpha} \qquad \ldots (2.4.11)$$

It is important to note that the net force or torque acting on the disc is same at every instant. The action of relay under such force is free from vibrations.

It can be observed from the equation (2.4.10) that if α is zero then the net force is zero and disc cannot rotate. Hence there must exist a phase difference between the two fluxes. The torque is maximum when the phase difference α is 90°.

The direction of the net force which decides the direction of rotation of disc depends on which flux is leading the other. In practice various constructions are used to produce phase displacement between the two fluxes.

2.4.2 Shaded Pole Type Induction Relay

The construction of shaded pole induction relay is shown in the Fig. 2.4.2.

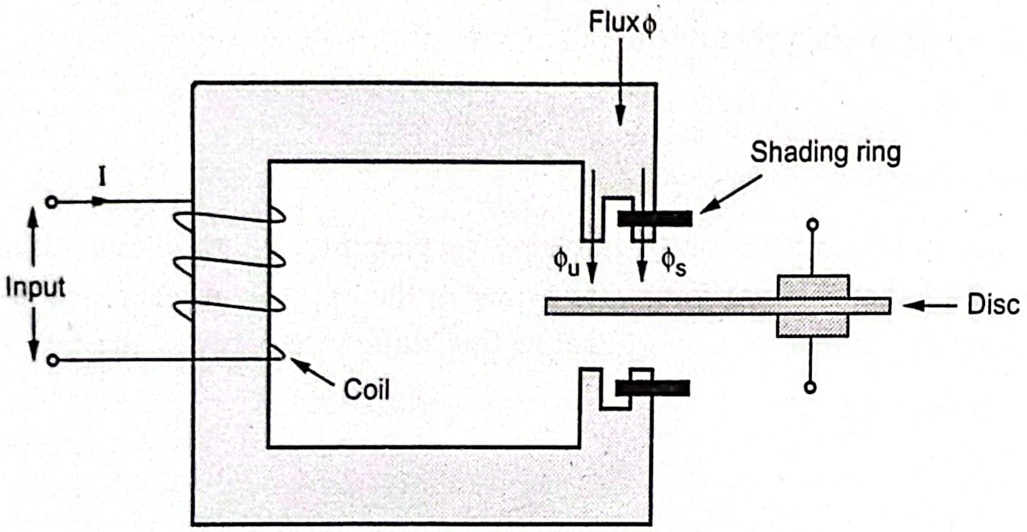


Fig. 2.4.2 Shaded pole type induction relay

It consists of an aluminium disc which is free to rotate in an air gap of an electromagnet. The part of pole face of each pole is shaded with the help of copper band or ring. This is called shading ring. The total flux ϕ produced due to the alternating current split into two fluxes displaced in time and space due to the shading ring.

Due to the alternating flux, e.m.f. gets induced in the shading ring. This e.m.f. drives the currents causing the flux to exist in shaded portion. This flux lags behind the flux in the unshaded portion by angle α.

Let ϕ_s = Flux in shaded portion

ϕ_u = Flux in unshaded portion

E_s = E.M.F. induced in the disc due to ϕ_s

E_u = E.M.F. induced in the disc due to ϕ_u

I_s = Induced current due to E_s

I_u = Induced current due to E_u

E_u lags behind ϕ_u by 90° while E_s lags behind ϕ_s by 90°. The current I_s lags E_s by small angle β while I_u lags E_u by small angle β. This angle is generally neglected and I_s and I_u are assumed to be in phase with E_s and E_u respectively, in practice. The phasor diagram is shown in the Fig. 2.4.3.

As proved in the previous section, neglecting β we get,

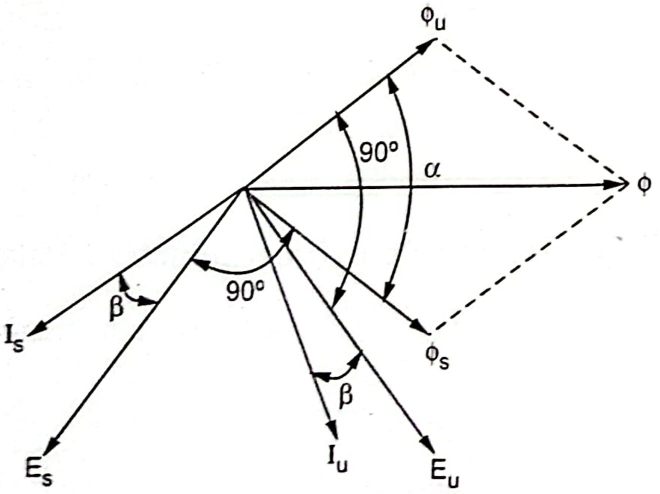


Fig. 2.4.3 Phasor diagram

$$T \propto \phi_s \phi_u \sin \alpha$$

where $T = \text{Torque}$

Assuming fluxes ϕ_s and ϕ_u to be proportional to the current I in the relay coil we can write,

$$T \propto I^2 \sin \alpha$$

$$\therefore \quad \boxed{T = kI^2} \quad \ldots k = \text{Constant}$$

As sin α is constant for the given design. Thus the torque is proportional to the square of the current through the coil.

2.4.3 Watthour Meter Type Induction Relay

The construction of this type of relay is similar to the watthour meter which is very popularly used everywhere. Thus relay has double winding structure. The arrangement is shown in the Fig. 2.4.4.

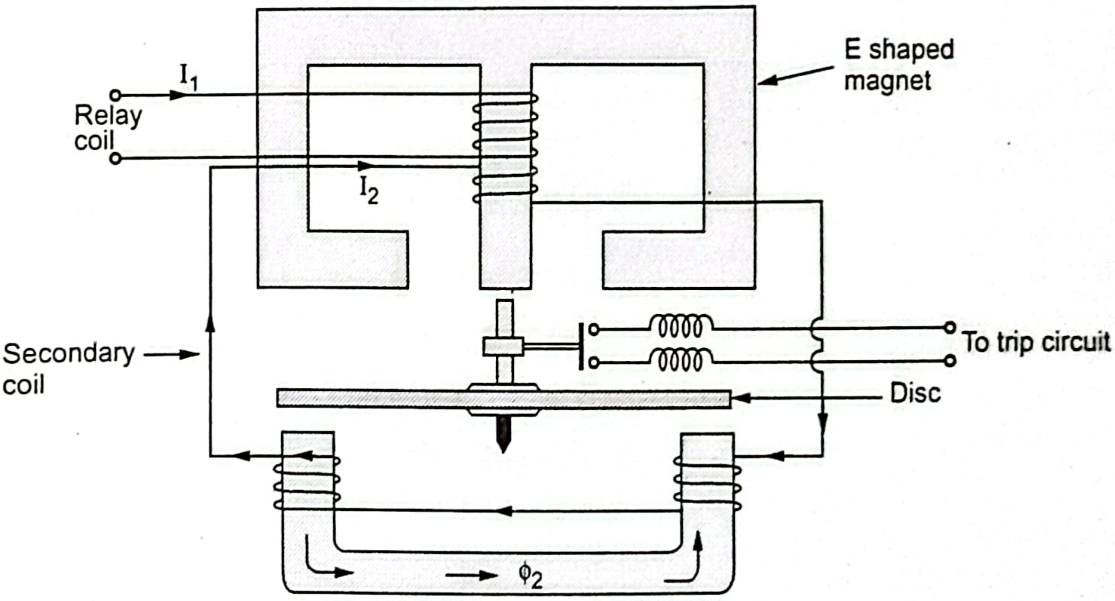


Fig. 2.4.4 Watthour meter type induction relay

It consists of two magnets, one E shaped magnet and other U shaped magnet. The disc is free to rotate in between these two magnets. The upper E shaped magnet carries both primary winding which is relay coil and the secondary winding. The primary carries the relay current I_1 which produces the flux ϕ_1. The e.m.f. gets induced in the secondary due to this flux. This drives current I_2 through secondary. Due to this current I_2, flux ϕ_2 gets produced in the lower magnet. This flux lags behind the main flux ϕ_1 by an angle α. Due to the interaction of these two fluxes, the torque is exerted on the disc and disc rotates.

Assuming that the entire flux ϕ_1 enters the disc from upper magnet and entire flux ϕ_2 enters the disc from lower magnet, we can write,

$$T \propto \phi_1 \phi_2 \sin \alpha$$

In this relay, the tapping can be provided on the primary. With the help of this suitable number of primary turns can be selected and hence current setting can be adjusted.

Most of the induction relays are of this type. An important feature of this relay is that its operation can be controlled by opening or closing of the secondary winding. It is opened, no current can flow through secondary hence flux ϕ_2 cannot be produced and hence no torque can be produced. Thus relay can be made inoperative opening the secondary winding.

2.4.4 Induction Cup Type Relay

The construction of this type of relay is very similar to an induction motor. The arrangement is shown in the Fig. 2.4.5.

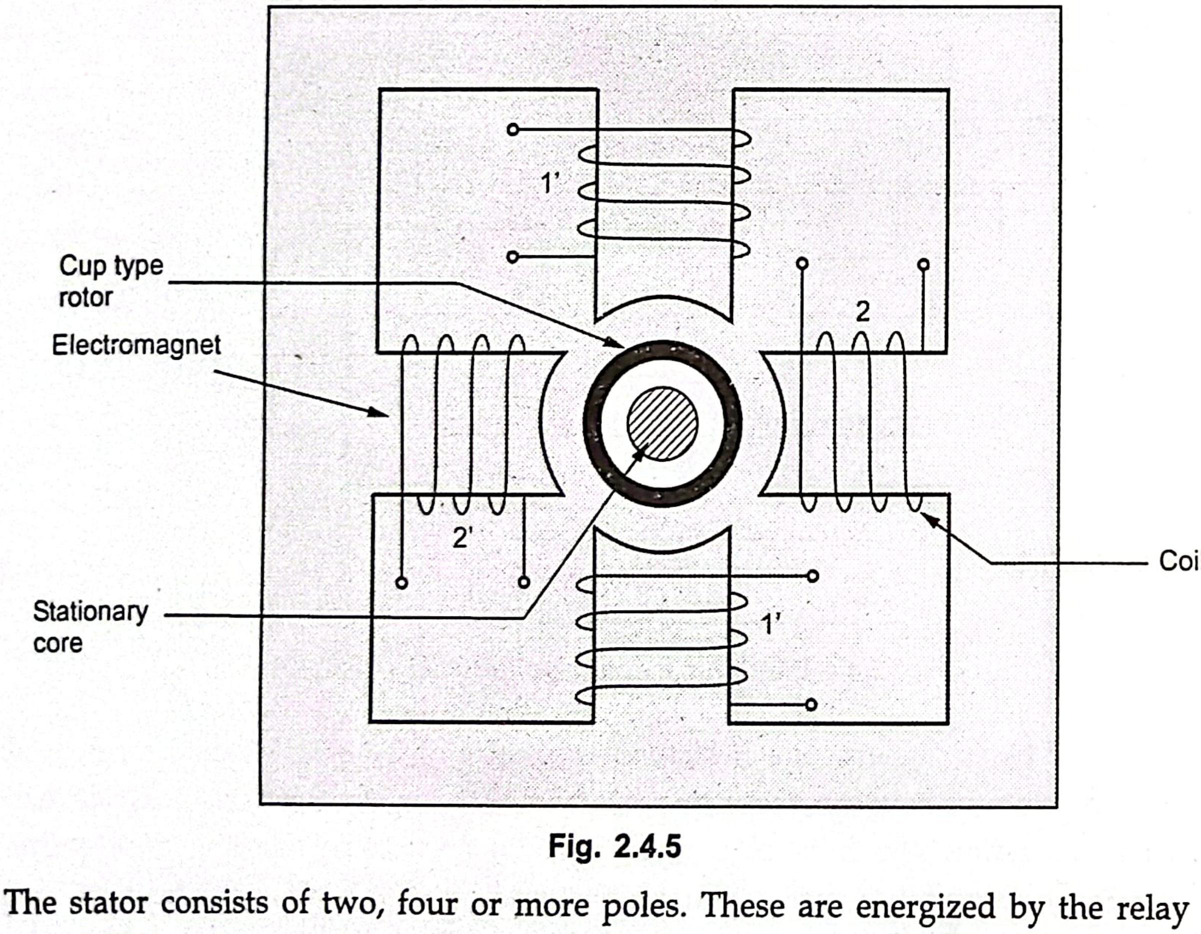


Fig. 2.4.5

The stator consists of two, four or more poles. These are energized by the relay coils. The Fig. 2.4.5 shows 4 pole structure and the two pairs of coils. The coils 1 and 1′ are connected while the coils 2 and 2′ are connected to form two pairs of coils. The rotor is hollow cylindrical cup type in structure. Compared to induction motor the difference is that in this relay the rotor core is stationary and only rotor conductor portion is free to rotate about its axis.

The currents and respective fluxes produced by the two pairs of coils are displaced from each other by angle α. Thus the resultant flux in the air gap is rotating. So rotating magnetic field is produced by two pairs of coils. Due to this, eddy currents are induced in the cup type rotor. These currents produce the flux. The interaction of the two fluxes produce the torque and the rotor rotates in the same direction as that of rotating magnetic field. A control spring and the back stop carried on an arm attached to the spindle of the cup, are responsible to prevent continuous rotation.

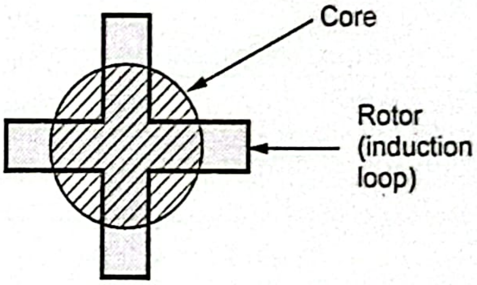


Fig. 2.4.6 Double induction loop structure

These relays are very fast in operation. The operating time of the order of 10 milliseconds is possible with this type. This is because the rotor is light having very low moment of inertia. The induction cup structure can be used for two quantity or single quantity relays. A single quantity relay means both the coils are fed by the same actuating quantity with a fixed phase angle shift in between them. To reduce the rotor inertia and to make the operation more fast, double induction loop structure is used. Such a structure is shown in the Fig. 2.4.6.

In all, the induction relays are widely used for protective relays involving a.c. quantities. High, low and adjustable speeds are possible in these relays. Various shapes of time against operating quantity curves can be obtained.

Review Questions

1. *Discuss about wattmeter type induction disc type relay.*
2. *Draw a neat diagram of induction cup type relay and explain its operating principle.*
3. *Discuss about shaded pole type induction relay.*
4. *How is the torque produced in induction type relays ? Derive the torque equation.*

AU : May-11, Marks 8

2.5 Universal Relay Torque Equation

AU : May-13

Most of the protection relays consist of some arrangement of electromagnets with armature or induction disc, which carry contacts. The relays also carry the closing or opening of contacts control devices like trip coils of circuit breaker. The electromagnets have current, voltage or both the types of windings. Currents through windings produce magnetic fluxes and torque is developed by the interaction between the fluxes of same windings or between the fluxes of both the windings. In general the torque produced by current winding is proportional to square of the current the torque produced by voltage winding is proportional to square of the voltage, and the torque produced by both the windings is proportional to product of voltage and the current. Mathematically we can write,

Torque produced by current coil = $K_1 I^2$

Torque produced by voltage coil = $K_2 V^2$

Torque produced by both the coils = $K_3 VI \cos(\theta - \tau)$

where K_1, K_2 and K_3 = Constant

θ = Angle between V and I

τ = Maximum torque angle

Torque produced by control spring = K_4

The control springs are used as restraining elements.

If all the elements are present in a relay then total torque produced by all the causes can be expressed by a general equation as,

$$T = K_1 I^2 + K_2 V^2 + K_3 VI \cos(\theta - \tau) + K_4$$

This equation is called universal relay torque equation the term K_4 can be a restraining torque due to springs or gravity.

By assigning positive and negative signs to certain constants and lets other constants to be zero and sometimes by adding similar other terms, the operating characteristics equation of all the types of protective relays can be obtained from universal equation.

For example, for overcurrent relay $K_2 = K_3 = 0$ and the spring torque is negative so we get,

$$T = K_1 I^2 - K_4$$

For the directional relay $K_1 = K_2 = 0$ and the spring torque is negative .

So we get,

$$\boxed{T = K_3\ VI \cos(\theta - \tau) - K_4}$$

Review Question

1. *What is universal relay torque equation ? What is its use ?* **AU : May-13, Marks 4**

2.6 Introduction to Overcurrent Relays

AU : May-12, Dec.-14,18

The overcurrent relays are classified depending upon the time of operation. These relays are classified as.

1. Instantaneous overcurrent relays : As the name indicates, these relays operate very fast and there is no intentional time delay provided in these relays. The operating time of these relays can be as low as 0.01 seconds. This speed of operation can be achieved by hinged armature type electromagnetic relay. These relays are effective only when the impedance between the relay and the source Z_S is very small compared to the impedance of the protected section Z_l.

2. Inverse definite time relays : All the overcurrent relays have inverse time characteristics means as the fault current level increases, the operating time of the relay decreases. These characteristics are more inverse near the pickup value of the actuating quantity and become less inverse as it is increased. The nature of these characteristics can be obtained by using the suitable core and by varying the point of saturation of this core. If the saturation occurs at a very early stage, then the time of operation almost remains same over the entire working range of the relay. This is called **definite time characteristics.** This is shown by the curve 'a' in the Fig. 2.6.1.

3. Inverse Definite Minimum Time Relay (IDMT) : When the core saturates at later stage, then the operating time becomes approximately inversely proportional to the fault current near the pickup value and then becomes constant. The core saturation current is slightly higher than the pickup value of the current . This is called **Inverse Definite Minimum Time (IDMT) characteristics.**

This is shown by the curve 'b' in the Fig. 2.6.1.

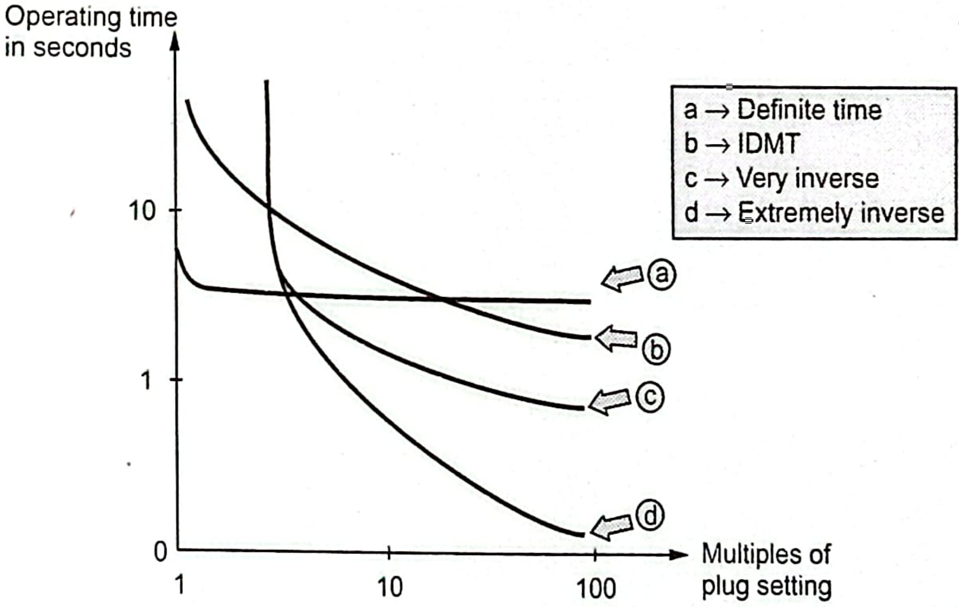


Fig. 2.6.1 Characteristics of various overcurrent relays

4. Very inverse relays : As the core saturation occurs at a further later stage then the inverse nature of characteristics continues for longer range and takes the shape indicated by the curve 'c' in the Fig. 2.6.1. This is called **very inverse time characteristics.** After saturation, the curve tends to definite time.

5. Extremely inverse relays : In such relays, the saturation occurs at very later stage and the curve has an inverse nature for almost entire working range. The mathematical equation for such characteristics is $I^2 t = K$ where I is the operating current and t is the operating time . This characteristics is called **extremely inverse time characteristics** and indicated by the curve 'd' in the Fig. 2.6.1.

Review Question

1. *What are the different inverse-time characteristics of overcurrent relays ? Explain in brief.*

AU : Dec.-14, 18, May-12, Marks 6

2.7 Nondirectional Induction Type Overcurrent Relay

AU : Dec.-04,06,07,10,17,18,22, May-05

This relay is also called earth leakage induction type relay.

The overcurrent relay operates when the current in the circuit exceeds a certain preset value. The induction type nondirectional overcurrent relay has a construction similar to a watthour meter, with slight modification. The Fig. 2.7.1 shows the constructional details of nondirectional induction type overcurrent relay.

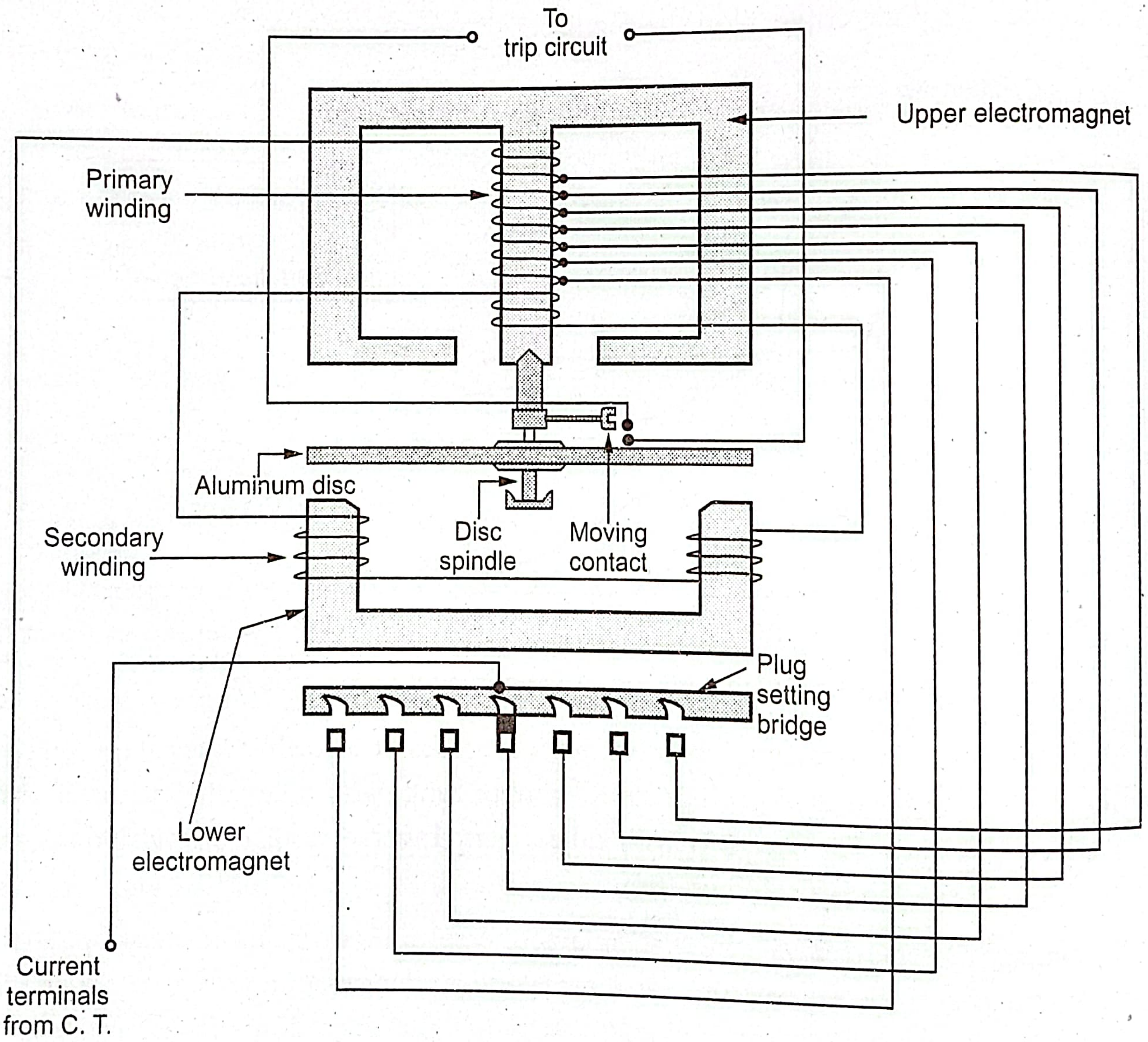

To
trip circuit
Upper electromagnet
Primary winding
Aluminum disc
Secondary winding
Disc spindle
Moving contact
Plug setting bridge
Lower electromagnet
Current terminals from C. T.

Fig. 2.7.1 Nondirectional induction overcurrent relay

It consists of two electromagnets. The upper is E shaped while the lower is U shaped. The aluminium disc is free to rotate between the two magnets. The spindle of the disc carries moving contacts and when the disc rotates the moving contacts come in contact with fixed contacts which are the terminals of a trip circuit.

The upper magnet has two windings, primary and secondary. The primary is connected to the secondary of C.T. on the line to be protected. This winding is tapped at intervals. The tappings are connected to plug setting bridge.

With the help of this bridge, number of turns of primary winding can be adjusted. Thus the desired current setting for the relay can be obtained. There are usually seven sections of tappings to have the overcurrent range from 50 % to 200 % in steps of 25 %. These values are percentages of the current rating of the relay. Thus a relay current rating may be 10 A i.e. it can be connected to C.T. with secondary current rating of 10 A but with 50 % setting the relay will start operating at 5 A. So adjustment of the current setting is made by inserting a pin between spring loaded jaw of the bridge socket, at the proper tap value required. When the pin is withdrawn for the purpose of changing the setting while relay is in service then relay automatically adopts a higher current setting thus secondary of C.T. is not open circuited. So relay remains operative for the fault occurring during the process of changing the setting.

The secondary winding on the central limb of upper magnet is connected in series with winding on the lower magnet. This winding is energized by the induction from primary. By this arrangement of secondary winding, the leakage fluxes of upper and lower magnets are sufficiently displaced in space and time to produce a rotational torque on the aluminium disc. The control torque is provided by the spiral spring.

When current exceeds its preset value, disc rotates and moving contacts on spindle make connection with trip circuit terminals. Angle through which the disc rotates is between 0° to 360°. The travel of the moving contacts can be adjusted by adjusting angle of rotation of disc. This gives the relay any desired time setting which is indicated by a pointer on a time setting dial. The dial is calibrated from 0 to 1. This does not give direct operating time but it gives multiplier which can be used along with the time-plug setting multiplier curve to obtain actual operating time of the relay. The time-plug setting multiplier curve is provided by the manufacturer.

2.7.1 Time - current Characteristics

Time required to rotate the disc depends on a torque. The torque varies as current in the primary circuit. More the torque, lesser is the time required hence relay has inverse time characteristics. The Fig. 2.7.2 shows the time-current characteristics for the overcurrent relay. Such characteristics are called Inverse Definite Minimum Type (I.D.M.T.) characteristics. This is because, the characteristics shows inverse relation between time and current for small values of currents. But as current increases, some definite time is required by the relay. So the characteristics becomes straight line for higher values of currents. Such I.D.M.T. characteristics can be obtained by saturating the iron in the upper magnet so that there cannot be increase in the flux once current achieves certain high value.

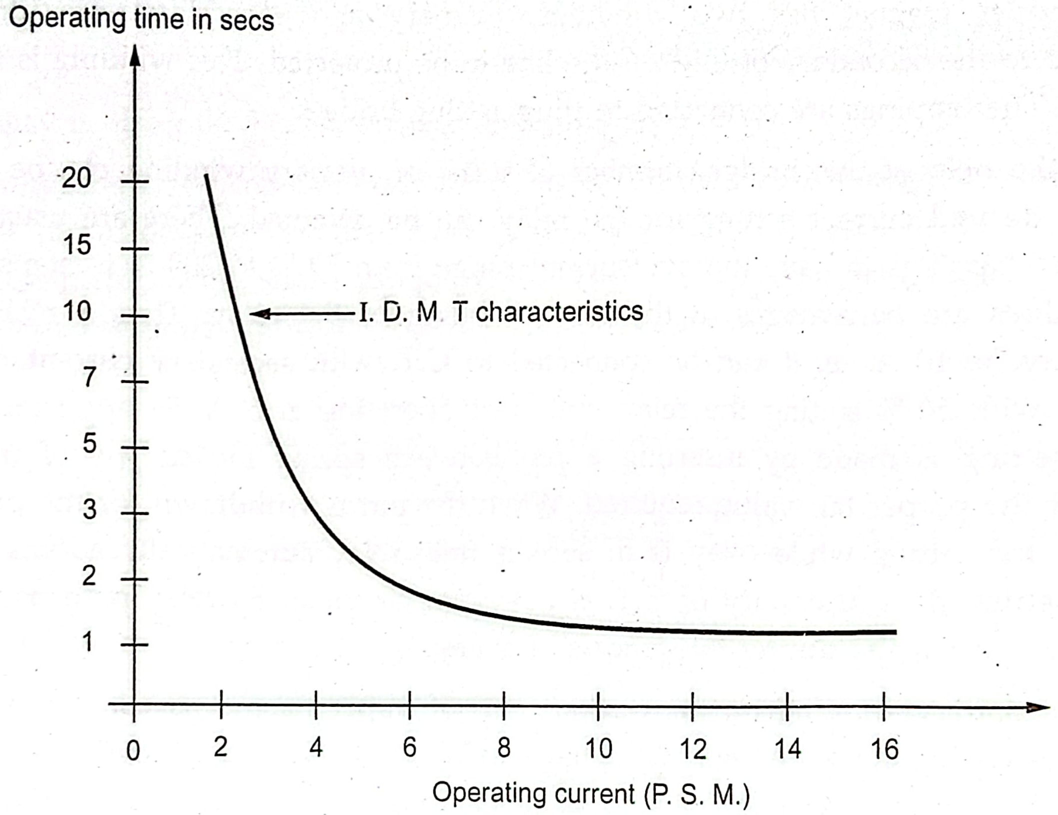


Fig. 2.7.2 Time-current characteristics

The P.S.M. can be obtained as,

$$\text{P.S.M.} = \frac{\text{Fault current in relay coil}}{\text{Rated secondary C.T. current} \times \text{Current setting}}$$

Fault current in relay coil = Line fault current × C.T. ratio

2.7.2 Operation

The torque is produced due to induction principle, as explained in the section 2.4.1. This torque is opposed by restraining force produced by spiral springs. Under normal conditions the restraining force is more than driving force hence disc remains stationary. Under fault conditions when current becomes high, the disc rotates through the preset angle and makes contact with the fixed contacts of trip circuit. The trip circuit opens the circuit breaker, isolating the faulty part from rest of the healthy system.

2.7.3 Calculation of Relay Operating Time

Practically, it is necessary to calculate the actual operating time of the relay, under the specific fault current levels. For these calculations, the following parameters related to the relay must be known.

1. Time/P.S.M. curve or tabular data.
2. Current setting.
3. Time setting multiplier.
4. Level of fault current.
5. Corresponding C.T. ratio.

The relay operating time can be obtained as,

1. Using the C.T. ratio, convert the fault current level to relay coil current level.
2. Calculate the plug setting multiplier from the relay coil current and current setting.
3. From the Time/P.S.M. curve on data, obtain the time corresponding to the plug setting multiplier calculated above.
4. Multiplying the time obtained by time multiplier setting, the actual relay time can be obtained.

Example 2.7.1 *An I.D.M.T. overcurrent relay has a current setting of 150 % and a time multiplier setting of 0.6. The primary of relay is connected to secondary of C.T. having ratio 400/5. Calculate the time of operation if the circuit carries a fault current of 5000 A. The time-current characteristics of the relay is shown in the Fig. 2.7.3.*

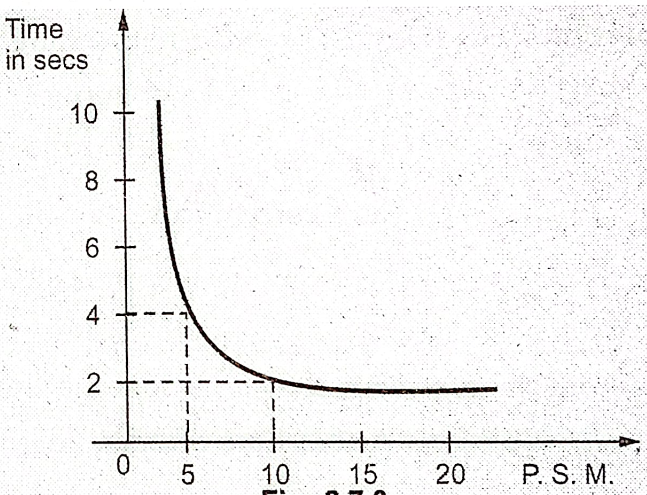


Fig. 2.7.3

Solution : Let us calculate P.S.M. first.

$$\text{Fault current in relay coil} = \text{Actual fault current} \times \text{C.T. ratio}$$

$$= 5000 \times \frac{5}{400} = 62.5 \text{ A}$$

Rated secondary of C.T. = 5 A

Current setting = 150 % = 1.5

$$\therefore \quad \boxed{\text{P.S.M.} = \frac{62.5}{5 \times 1.5} = 8.333}$$

From Fig. 2.7.3, approximate time for P.S.M. of 8.33 is 1.8 sec.

∴ Actual operation time = 1.8 × Time setting multiplier

= 1.8 × 0.6 = **1.08 seconds**

Example 2.7.2 *The Fig. 2.7.4 shows the part of a typical power system. If for the discrimination, the time grading margin between the relays is 0.6 sec, calculate the time of operation of relay 1 and time setting multiplier for relay 2. Refer to characteristics given in the Fig. 2.7.3. The time setting multiplier of relay 1 is 0.3.*

AU : May-22, Dec.-22, Marks 15

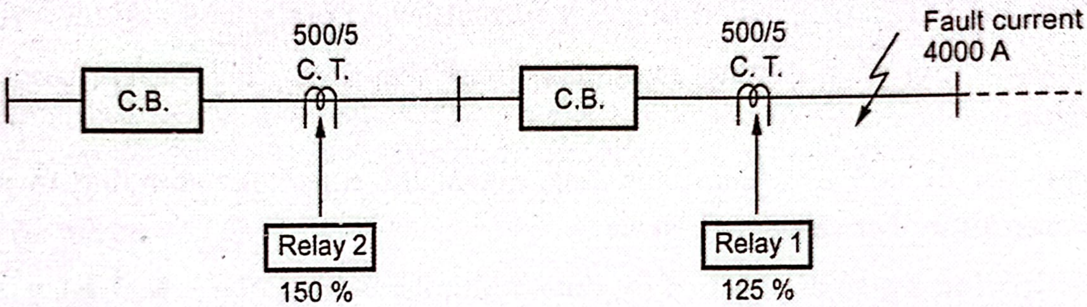


Fig. 2.7.4

Solution : For relay 1 : Current setting = 125 % = 1.25

Fault current = 4000 A

C.T. ratio = 500/5

∴ Fault current in relay coil $= 4000 \times \frac{5}{500} = 40$ A

∴ $$\text{P.S.M.} = \frac{40}{5 \times 1.25} = 6.4$$

From the Fig. 2.7.3, the corresponding time for 6.4 P.S.M. is approximately 3 sec.

∴ Actual time of operation = 3 × Time setting multiplier = 3 × 0.3

= **0.9 sec**

For relay 2 : Current setting = 150 % = 1.5

Actual time of operation = Time of operation of relay 1 + Time margin

= 0.9 + 0.6 = 1.5 sec

Fault current $= 4000 \times \frac{5}{500} = 40$ A

∴ $$\text{P.S.M.} = \frac{\text{Fault current}}{\text{C.T. secondary rating} \times \text{Current setting}}$$

$$= \frac{40}{5 \times 1.5} = 5.33$$

From the Fig. 2.7.3, the corresponding time for 5.33 P.S.M. is approximately 3.8 sec.

$$\therefore \quad \text{Time setting multiplier} = \frac{\text{Actual time of operation}}{\text{Time for P.S.M. obtained}}$$

$$= \frac{1.5}{3.8} = 0.395 \approx \mathbf{0.4}$$

This is the required time setting multiplier for the relay 2.

Example 2.7.3 *The current rating of a relay is 5 A. PSM = 1.5, CT ratio 400/5, fault current = 6000 A. Determine the operating time of the relay for a TMS = 0.4. At TMS = 1, the operating time at various PSM are :*

PSM	2	4	5	8	10	20
Operating time (s)	10	5	4	3	2.8	2.4

Solution : Fault current = 6000 A, C.T. ratio = 400/5

$$\text{Fault current in relay} = 6000 \times \frac{5}{400} = 75 \text{ A}$$

$$\text{Rated secondary of C.T.} = 5 \text{ A}$$

$$\text{Current setting} = 1.5 \quad \text{i.e.} \quad 150 \%$$

$$\therefore \quad \text{P.S.M.} = \frac{\text{Relay fault current}}{\text{Rated current} \times \text{Current setting}} = \frac{75}{5 \times 1.5} = 10$$

From the given table, the operating time for P.S.M. = 10 is 2.8 sec.

$$\therefore \quad \text{Actual operating time} = \text{Time} \times \text{Time multiplier setting}$$

$$= 2.8 \times 0.4 = \mathbf{1.12 \text{ sec}}$$

Review Questions

1. *Explain with the help of neat circuit diagram, the principle of operation of an induction type overcurrent relay. Explain its IDMT characteristics and discuss how these characteristics are obtained in an induction relay.* **AU : Dec.04, 06, 07, 10, 17, 18, May-05, Marks 12**

2. *An I.D.M.T. overcurrent relay has a current setting of 150 % and has a time multiplier setting of 0.5. The relay is connected in the circuit with the help of C.T. having ratio 500 : 5 A. Calculate the time of operation of the relay if circuit carries a fault current of 6000 A. The relay characteristics are given in the Fig. 2.7.5.*

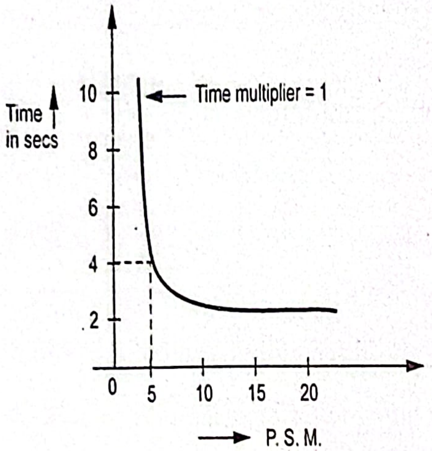


Fig. 2.7.5 Relay characteristics

3. *For a particular transmission line, relays are used as shown in the Fig. 2.7.6.*

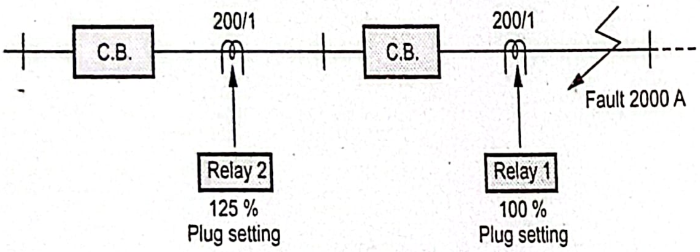


Fig. 2.7.6

For discrimination, the time grading margin is 0.5 sec. Determine the time of operation of the two relays assuming that both the relays have characteristics as shown in the Fig. 2.7.6. The relay 1 has time setting multiplier of 0.2. Find the time setting multiplier of relay 2.

[Ans. : 0.56 sec, 1.06 sec, 0.3364]

4. *The current ratings of an overcurrent relay is 5 A. It has a PSM = 2, TSM = 0.3, CT ratio = 400/5, fault current = 4000 A. Determine the time of operations of the relay assuming normal IDMT characteristics.* **[Ans. : 1.2 sec]**

5. *Determine the actual time of operation of a 5 ampere, 3 second over current relay having a current setting of 125 % and a time setting multiplier of 0.6 connected to supply circuit through a 400/5 current transformer when the circuit carries a fault current of 4000 A. Time of operation is 3.5 seconds for the estimated value of PSM.* **[Ans. : 2.1 s]**

6. *With neat diagram, explain the construction and operation of non directional over current relay.* **AU : Dec.-22, Marks 13**

2.8 Directional Power Relay

AU : May-08,13, Dec.-18

The directional relay means the relay operates for the specific direction of the actuating quantity in the circuit. The directional power relay operates when power in the circuit flows in the specific direction. The construction and principle of operation of this relay is similar to the induction type watthour meter relay. The difference is that in watthour meter type relay the torque is produced due to interaction of the fluxes produced by only the current derived from secondary of C.T. while in directional power relay the torque is produced due to interaction of the fluxes produced from both voltage and current of the circuit. The relay has two windings, one acts as voltage coil while other as current coil, similar to a wattmeter. The upper magnet carries a voltage coil or potential coil which is energized from P.T. while the lower magnet carries a current coil which is energized from C.T. in the line to be protected. The construction is shown in the Fig. 2.8.1.

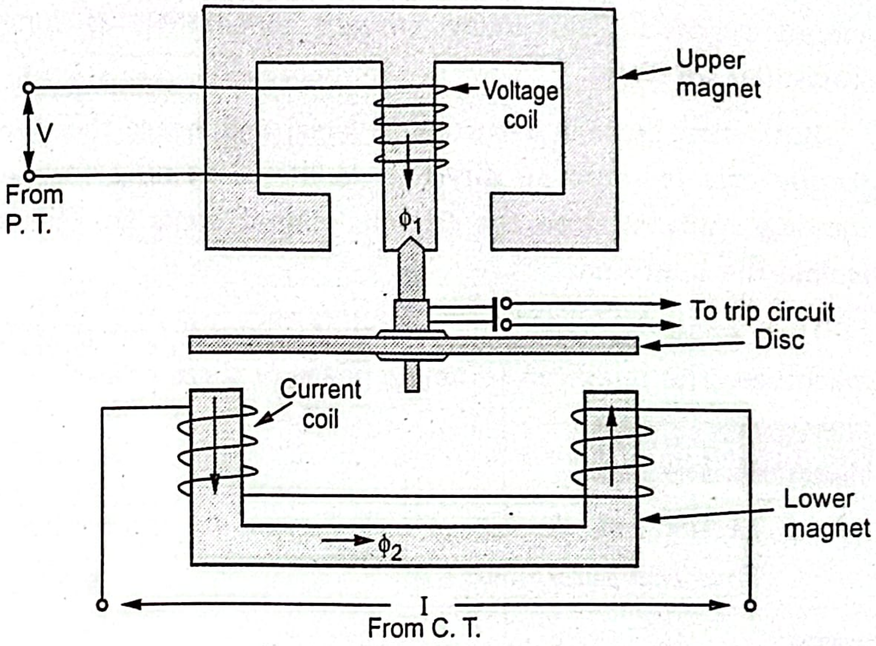


Fig. 2.8.1 Directional power relay

The number of tappings are provided to the current coil with which desired current setting can be achieved. The restraining torque is provided by the spiral spring. The spindle of disc carries the moving contacts which make contact with tripping circuit terminals when the disc rotates. The voltage coil provided on the upper magnet produces the flux ϕ_1. This lags the voltage V by 90 °. The current I is sensed by the current coil on lower magnet which produces the flux ϕ_2. This is in phase with current I. The current I lags voltage V by an angle ϕ. The angle between ϕ_1 and ϕ_2 is α as shown in the phasor diagram in the Fig. 2.8.2.

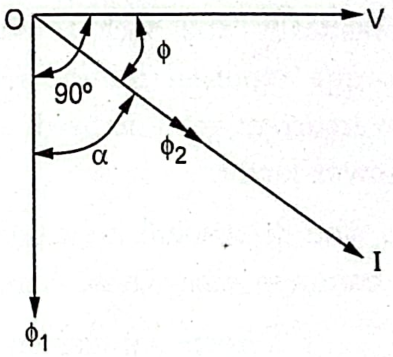


Fig. 2.8.2

The interaction of fluxes ϕ_1 and ϕ_2 produces the torque. Hence we can write,

$$T \propto \phi_1 \phi_2 \sin \alpha$$

But $\phi_1 \propto V$ and $\phi_2 \propto I$

while $\alpha = 90 - \phi$

$\therefore$ $T \propto VI \sin(90 - \phi)$

$\therefore$ $\boxed{T \propto VI \cos \phi \propto \text{Power in circuit}}$

Under normal working conditions, the driving torque acts in the same direction as that of restraining torque. This moves the moving contacts away from the fixed tripping circuit contacts. Thus relay remains inoperative as long as power flow is in one particular direction.

But when there is a current reversal and hence the power reversal then the driving torque acts in opposite direction to the restraining torque in such a manner that the moving contacts close the tripping circuit contacts. This opens the circuit breaker to isolate the faulty part.

This relay is used for providing the reverse power protection to synchronous machines. The relay can be single phase or three phase.

Review Question

1. *Explain with the help of neat diagram the construction and working of induction type directional power relay.* **AU : May-08, 13, Dec.-18, Marks 8**

2.9 Directional Induction Type Overcurrent Relay

AU : May-04,05,07,14,19,22, Dec.-11,12,13,14,15,16,18

The directional power relay is not suitable to use as a protective relay under short circuit conditions. This is because under short circuit conditions the voltage falls drastically and such a reduced voltage may not be sufficient to produce the driving torque required for the relay operation. Hence in practice, directional induction type overcurrent relay is used. This relay operates almost independent of system voltage and power factor.

The directional induction type overcurrent relay uses two relay elements mounted on a common case. These elements are,

1. Directional element which is directional power relay
2. Nondirectional element which is nondirectional overcurrent relay.

The schematic arrangement of such a directional relay is shown in the Fig. 2.9.1. (See Fig. 2.9.1 on next page).

Directional element : The directional element is nothing but a directional power relay which operates when power in the circuit flows in a particular direction. The voltage coil of this element is energized by a system voltage through a potential transformer. The current coil on the lower magnet is energized by the system current through a current transformer. The trip contacts of this relay (1 – 1′) are connected in series with the secondary winding of nondirectional element.

Nondirectional element : The current coil of the directional element is connected in series with the primary winding of nondirectional element. The plug setting bridge is provided in this element to adjust current setting as per the requirement. The trip contacts (1 – 1′) are in series with winding on lower magnet of nondirectional element.

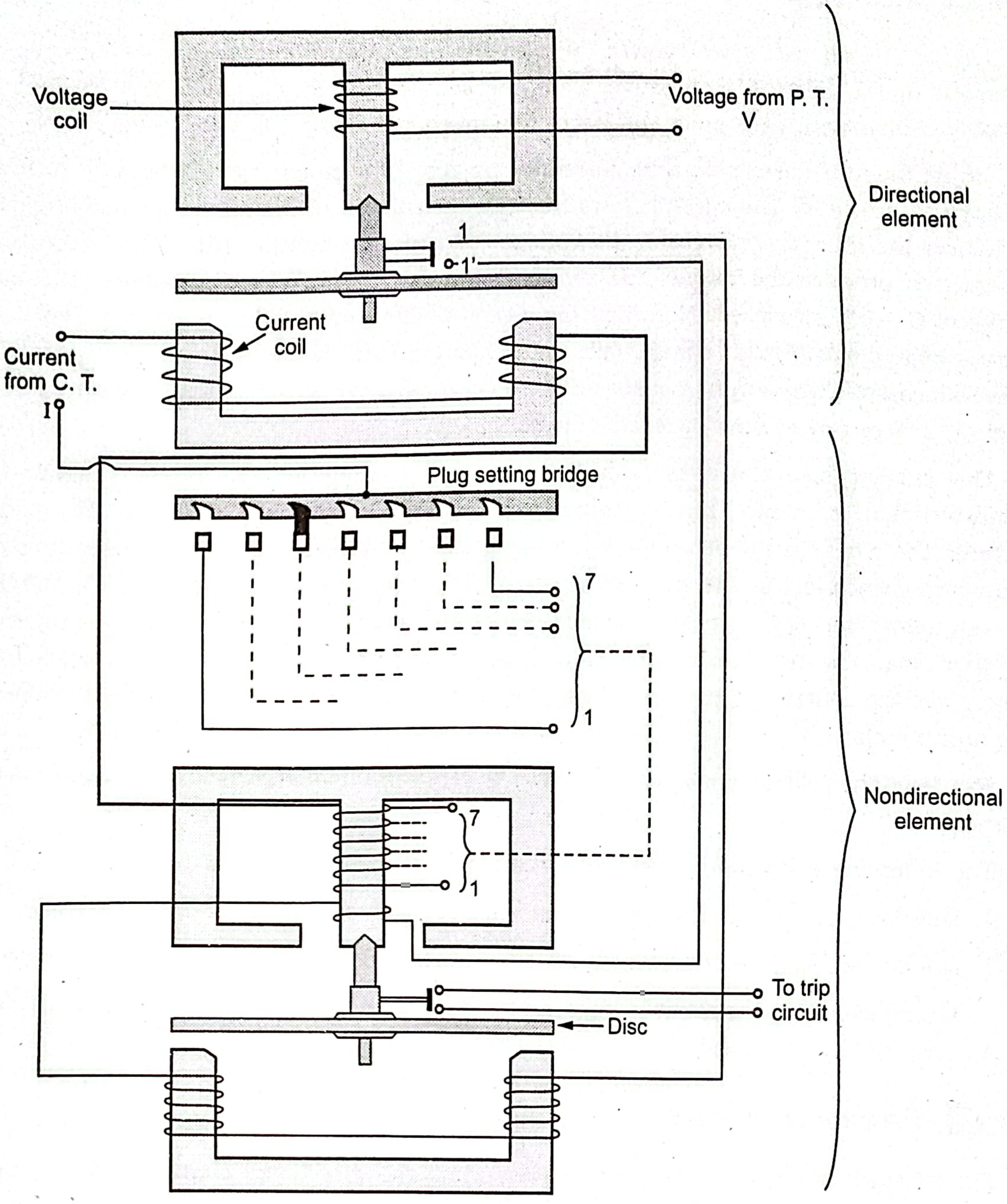

Voltage coil
Voltage from P. T.
V
Directional element
1
1'
Current coil
Current from C. T.
I
Plug setting bridge
7
1
Nondirectional element
7
1
To trip circuit
Disc

Fig. 2.9.1 Directional overcurrent relay

So unless and until trip contacts (1 – 1′) are closed by the movement of the disc of directional element, the nondirectional element cannot operate. Thus the movement of the nondirectional element is controlled by the directional element.

2.9.1 Operation

Under normal conditions, power flows in the proper direction and hence directional element of the relay is inoperative. Thus the secondary winding on lower magnet of nondirectional element is open and hence nondirectional element is also inoperative.

When the fault takes place, the current or power in the circuit has a tendency to flow in reverse direction. The current flows through current coil of directional element which produces the flux. The current in the voltage coil produces another flux. The two fluxes interact to produce the torque due to which the disc rotates. As disc rotates, the trip contacts (1 – 1′) get closed. Note that the design of directional element is such that it is very sensitive and though voltage falls under short circuit, the current coil is responsible to produce sufficient torque to have disc rotation. It is so sensitive that it can operate even at 2 % of power flow in reverse direction.

The current also flows through the primary winding on the upper magnet of nondirectional element. Thus energizes the winding to produce the flux. This flux induces the e.m.f. in the secondary winding of the nondirectional element according to induction principle. As the contacts (1 – 1′) are closed, the secondary winding has a closed path. Hence the induced e.m.f. drives the current through it, producing the another flux. The two fluxes interact to produce the driving torque which rotates the disc. Thus the contacts of trip circuit get closed and it opens the circuit breaker to isolate the faulty section.

So directional element must operate first to have the operation of the nondirectional element.

The following **conditions** must be satisfied to have the operation of the entire relay :

1. The direction of current in the circuit must reverse to operate directional element.
2. The current value in the reverse direction must be greater than the current setting.
3. The high value of current must persist for a time period which is greater than the time setting of the relay.

2.9.2 Directional Characteristics (Torque Equation)

Let us study the phasor diagram to understand the directional characteristics of the relay.

Let V = Relay voltage through P.T.

I = Relay coil current through C.T.

θ = Angle between V and I

Note The system current is generally lagging the voltage but with suitable connection the relay current is made to lead the voltage by angle θ.

Due to this, the correct operation of relay at all the types of faults under all system condition is ensured.

So current I leads voltage V by angle θ.

ϕ_V = Flux produced by voltage V

This flux ϕ_V lags voltage V by an angle ϕ.

ϕ_I = Flux produced by current I

The flux ϕ_I is in phase with the current I.

The phasor diagram is shown in the Fig. 2.9.2. The voltage V is taken as reference.

The torque is proportional to the fluxes ϕ_V, ϕ_I and sine of the angle between the two fluxes.

$$\therefore \quad T \propto \phi_V \phi_I \sin(\phi_V \hat{\ } \phi_I)$$

$$\propto \phi_V \phi_I \sin(\theta + \phi)$$

Now $\quad \phi_V \propto V \quad$ and $\quad \phi_I \propto I$

$$\therefore \quad \boxed{T = KVI \sin(\theta + \phi)}$$

where $\quad K$ = Constant

Maximum torque occurs when $\sin(\theta + \phi)$ is 1 i.e.

$$\theta + \phi = 90°$$

The condition for the maximum torque is shown dotted in the Fig. 2.9.2.

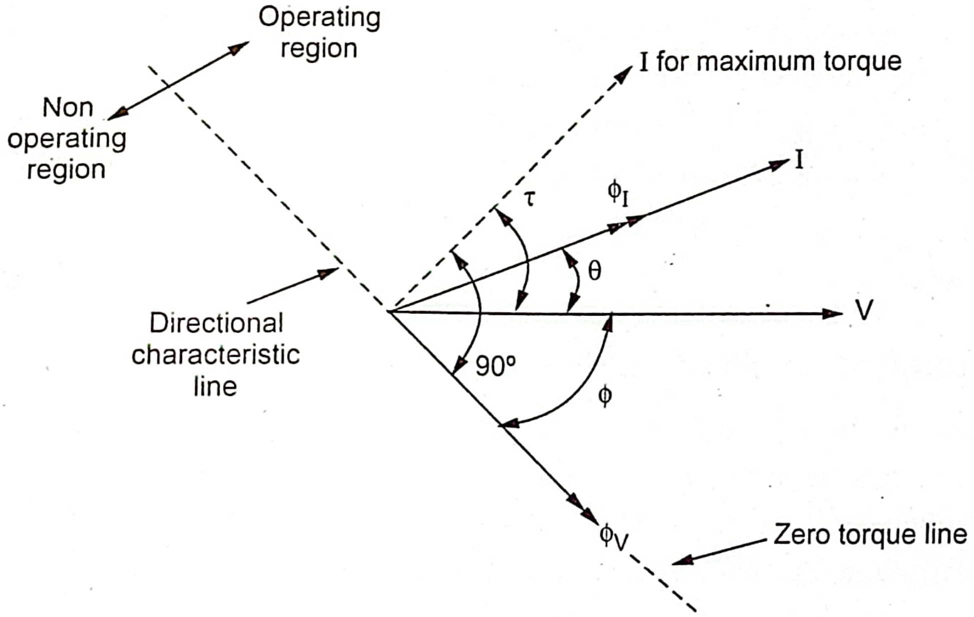


Fig. 2.9.2 Phasor diagram and directional characteristic

This will be satisfied when the relay current I phasor lies along the ϕ_V phasor or in antiphase with ϕ_V. The corresponding line is called zero torque line and is shown in the Fig. 2.9.2. This line is at right angles to the maximum torque condition line.

Thus the directional element operates, provided that the current phasor lies within ±90° of the maximum torque line. If it is displaced more than 90 ° then the element will restrain. Both operating as well as nonoperating regions are shown in the Fig. 2.9.2.

Maximum torque angle : The angle by which the current supplied to the relay leads the voltage supplied to the relay so as to obtain the maximum torque is called Maximum Torque Angle (M.T.A.). It is denoted as τ in the Fig. 2.9.2.

From the Fig. 2.9.2, we can write,

$$\phi = 90° - \tau$$

Substituting in the torque equation,

$$T = KVI \sin(\theta + 90° - \tau)$$

$$\therefore \quad \boxed{T = KVI \cos(\theta - \tau)}$$

This is the torque equation interms of maximum torque angle τ. The typical values of the maximum torque angle are 0 °, 30 °, 45 ° etc.

Review Questions

1. *Describe the construction and operation of an inductive type directional over current relay with neat diagram. Also explain its operational characteristics. Derive the torque equatiion.* **AU : May-04,05,07,19, Dec.-11,13,15,16,18, Marks 16**
2. *Describe the operating principle, constructional features and application of directional relay. How do you implement directional feature in the over current relay ?* **AU : May-14, Dec.12, Marks 16**
3. *Describe the techniques used to realize various time-current characteristics using electromechanical relays. Also, compare the time-current characteristics of inverse, very inverse and extremely inverse over current relays. Discuss their applications.* **AU : Dec.-14, Marks 16**
4. *Describe the construction and principle of operation of an induction type directional over current relay.* **AU : May-22, Marks 13**

2.10 Introduction to Distance Relays

In the relays discussed uptil now, the operation of the relays is dependent on the magnitude of the current or voltage of the circuit to be protected. In distance relays, the operation is dependent on the ratio of the voltage and current, which is expressed interms of an impedance. Hence basically distance relays are called impedance relays. The impedance is nothing but an electrical measure of distance along a transmission line. The relay operates when the ratio V/I i.e. impedance is less than a predetermined value. As the ratio V/I affects the performance of these relays, the relays are also called ratio relays. Dependent on the ratio of V and I there are three types of distance relays which are,

1. Impedance relay which is based on measurement of impedance Z.
2. Reactance relay which is based on measurement of reactance X.
3. Admittance or Mho relay which is based on measurement of component of admittance Y.

In short, a distance relay is one whose performance is based on the measurement of impedance, reactance or admittance of line between the location of relay and the point where fault occurs.

Review Question

1. *What is a distance relay ?*

2.11 Impedance Relay

AU : May-06,08,12,13,17,18,22, Dec.-06,11,13,14,15,16

The impedance relay works corresponding to the ratio of voltage V and current I of the circuit to be protected. There are two elements in this relay, the one produces a torque proportional to current while the other produces a torque proportional to voltage. The torque produced by the current element is balanced against torque produced by the voltage element. Thus the current element produces operating torque, pickup torque which can be said to be positive torque. The voltage element produces restraining torque, reset torque which can be said to be negative torque. So this relay is voltage restrained overcurrent relay.

The Fig. 2.11.1 shows the basic operating principle of an impedance relay.

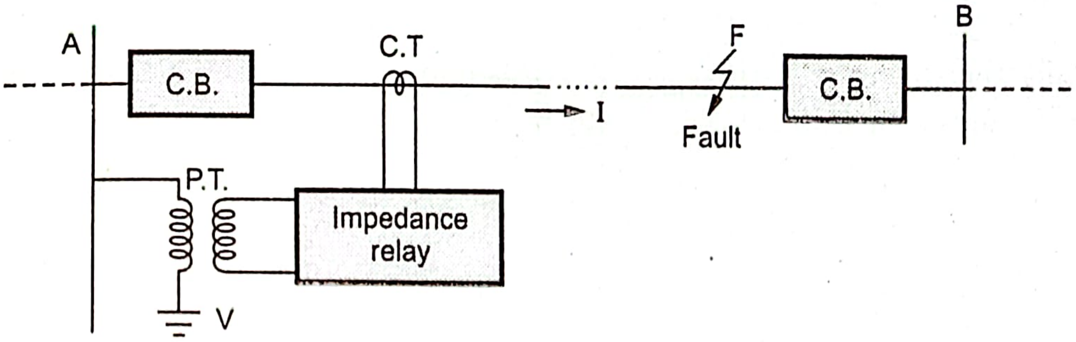


Fig. 2.11.1 Basic operation of impedance relay

The current element is energized by current through C.T. while voltage element is energized by voltage through P.T. The section AB of the line is protected zone.

Under normal conditions, the ratio of voltage V and current I is denoted as Z_L which is impedance of line. The relay is inoperative under this condition.

When the fault occurs at point F in the protected zone then the voltage drops while current increases. Thus the ratio V/I i.e. the impedance reduces drastically. This is the impedance of line between the point at which relay is connected and the point F at which fault occurs. So when the impedance reduces than its predetermined value Z_L, it trips and makes the circuit breaker open.

2.11.1 Torque Equation

The positive torque produced by the current element is proportional to I^2 while the negative torque produced by the voltage element is proportional to V^2.

Let control spring effect produces a constant torque of $-K_3$.

Hence the torque equation becomes,

$$T = K_1 I^2 - K_2 V^2 - K_3 \quad \text{... (2.11.1)}$$

where K_1, K_2 are the constants, while V and I are r.m.s. values.

At the balance point, when the relay is on the verge of operating, the net torque is zero hence we can write,

$$0 = K_1 I^2 - K_2 V^2 - K_3$$

$$\therefore \quad K_2 V^2 = K_1 I^2 - K_3 \quad \text{... (2.11.2)}$$

Dividing both sides by $K_2 I^2$,

$$\frac{V^2}{I^2} = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2} \quad \text{i.e.} \quad Z^2 = \frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}$$

$$\therefore \quad \boxed{Z = \sqrt{\frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}}} \quad \text{... (2.11.3)}$$

Generally the spring effect is neglected as its effect is dominant at low currents which generally do not occur in practice. So with $K_3 = 0$,

$$\therefore \quad \boxed{Z = \sqrt{\frac{K_1}{K_2}} = \frac{V}{I} = \text{Constant}} \quad \text{... (2.11.4)}$$

2.11.2 Operating Characteristics

As seen from the equation (2.11.4), it can be stated that the impedance relay is on the verge of operating at a given constant value of the ratio V/I, which can be expressed as an impedance.

For a particular fault position, the ratio V/I i.e. impedance is constant. It changes if the fault position changes. If fault is nearer to relay, this ratio will be low and as fault position moves away from the relay the ratio becomes higher and higher. So it can be installed to operate for the section to be protected and once installed and adjusted for a particular section, it is inoperative beyond that section.

The operating characteristics of the relay is shown in the Fig. 2.11.2.

As the effect of spring is dominating for the lower values of currents, the characteristics shows a noticiable bend at lower currents.

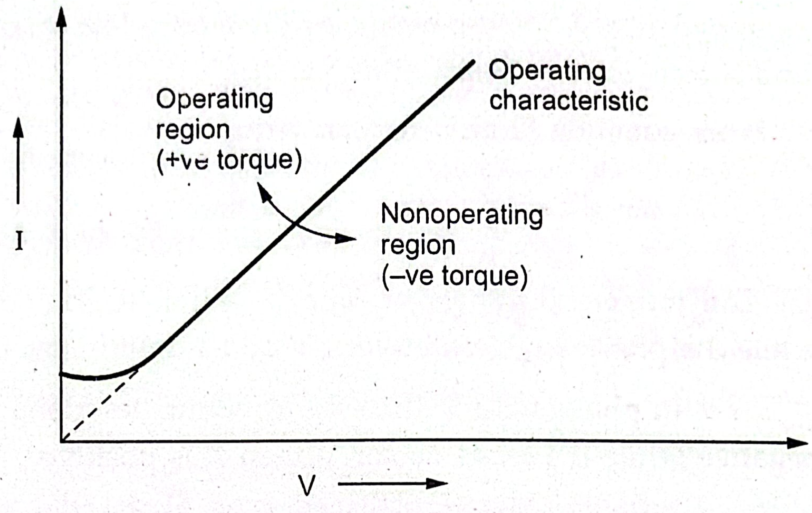


Fig. 2.11.2 Operating characteristics

But for all practical purposes, the dotted line, which represents a constant value of Z may be considered as an operating characteristics.

The impedance Z which is predetermined set value is given by,

$$\therefore \quad \boxed{Z = \frac{1}{\text{Slope of characteristics}}}$$

The relay will pickup for any combination of V and I represented by any point above the line in the positive torque region. In other words for any value of Z less than the constant value represented by the line, the relay will operate.

By adjustments, the slope of the characteristics can be changed so that the relay will respond to all the values of impedance less than any desired upper limit.

2.11.3 Operating Characteristics on R-X Diagram

The operating characteristics of an impedance relay can be more easily represented by a diagram called R-X diagram. The diagram is shown in a plane having X-axis as R (resistance) while the Y-axis as X (reactance). This plane is called R-X plane. The impedance Z can be expressed as,

$$Z = R + jX \qquad \text{i.e.} \qquad |Z| = \sqrt{R^2 + X^2}$$

$$\therefore \quad \boxed{Z^2 = R^2 + X^2} \qquad \ldots (2.11.5)$$

Mathematically $x^2 + y^2 = r^2$ represents an equation of circle where x and y are vertical and horizontal co-ordinates while r is the radius. Similarly the equation (2.11.5) represents circle where R and X are vertical and horizontal co-ordinates and magnitude of impedance $|Z|$ is the radius of the circle. The centre of this circle is at point where R and X axes intersect each other i.e. origin.

From equation (2.11.5) we can write,

$$\tan\phi = \frac{X}{R} \quad \text{i.e.} \quad \boxed{\phi = \tan^{-1}\frac{X}{R}} \qquad \ldots (2.11.6)$$

The numerical values of ratio V and I determine the length of the radius vector Z while the phase angle ϕ between V and I determines the exact position of the vector Z.

If I is in phase with V then the Z vector lies along R-axis. If I lags vector V then X is negative while if I leads vector V then X is positive.

The operation of the relay is independent of phase angle ϕ and hence the operating characteristic is a circle with radius equal to magnitude of Z which is predetermined set value.

At any value of Z less than the radius of the circle, the relay operates. Hence the entire portion inside the circle is **positive torque region** i.e. operating region of the relay while the portion exterior to the circle is **negative torque region** i.e. nonoperative region, as shown in the Fig. 2.11.3.

If Z_f = Impedance between relay and fault point

Z = Set value for impedance = Radius of circle

Then for, $Z_f < Z$ ... Relay operates

$Z_f > Z$ ... Relay is inoperative

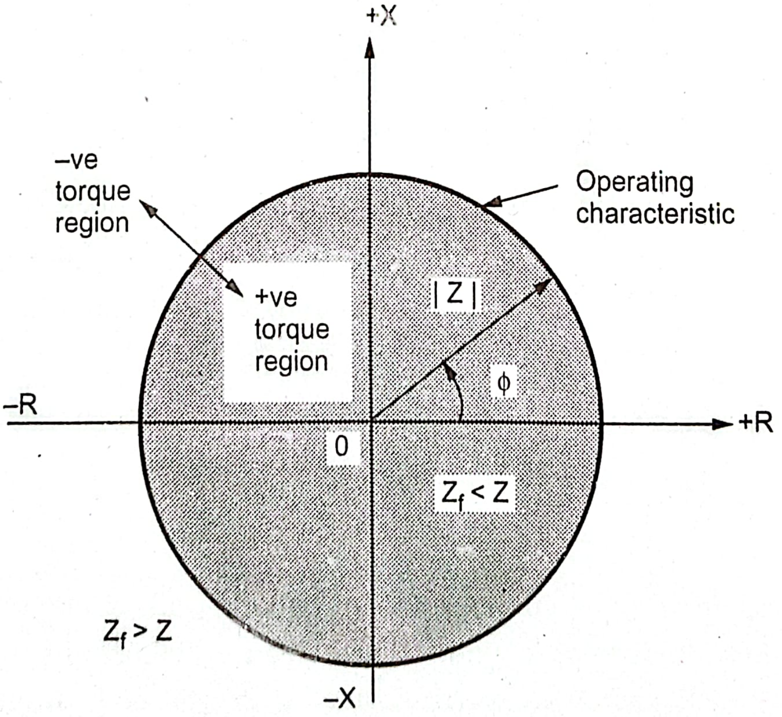


Fig. 2.11.3 Characteristic on R-X diagram

Such a relay is nondirectional and can operate for faults on either side of a point where relay is installed.

2.11.4 Disadvantages of Plain Impedance Relay

The plain impedance relay suffers from following disadvantages.

1. It is nondirectional and can operate for faults on both sides of a point where relay is connected. Hence it fails to discriminate between internal and external faults.
2. When fault occurs, an arc exists. The arc resistance of line fault affects the performance of this relay.
3. As a large area is covered by the circle on each side on R-X plane, the power swings also can affect the performance of this relay.

The nondirectional performance can be made directional by adding a directional element in the plain impedance relay.

2.11.5 Directional Impedance Relay

The directional impedance relay can be obtained by adding a directional element in the basic impedance relay. The element can sense the direction of power or current flow and relay can operate only if the direction of power flow is in one particular direction with respect to the point where relay is installed.

The characteristics of a directional element is a tilted straight line passing through origin, which can be shown in R-X diagram, as represented in the Fig. 2.11.4. The dotted line indicates the line of maximum torque. While the dotted portion shown above the line indicates the operating region of the directional element.

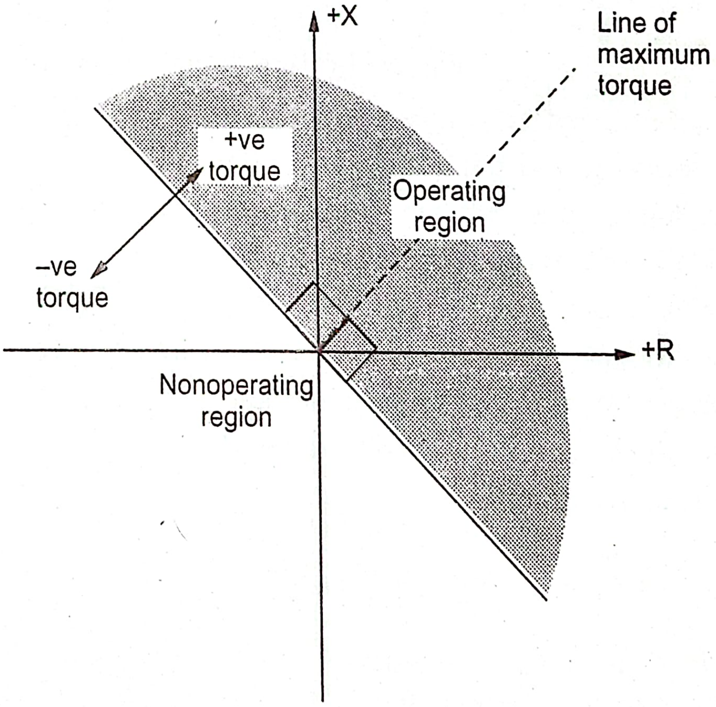


Fig. 2.11.4 Directional characteristics

Now such a pure directional element is added to the impedance relay, we get the resultant characteristics which is a combination of a straight line and a circle of radius |Z|. Thus the resultant characteristics obtained by superimposing the straight line characteristics of directional element on the circle of the impedance relay is shown in th Fig. 2.11.5. The relay trips for the points which are within the circle and above th directional characteristics. The operating region is just a **semicircle.** The shaded portion shown in the Fig. 2.11.5 is a positive torque region i.e. the operating region of the relay.

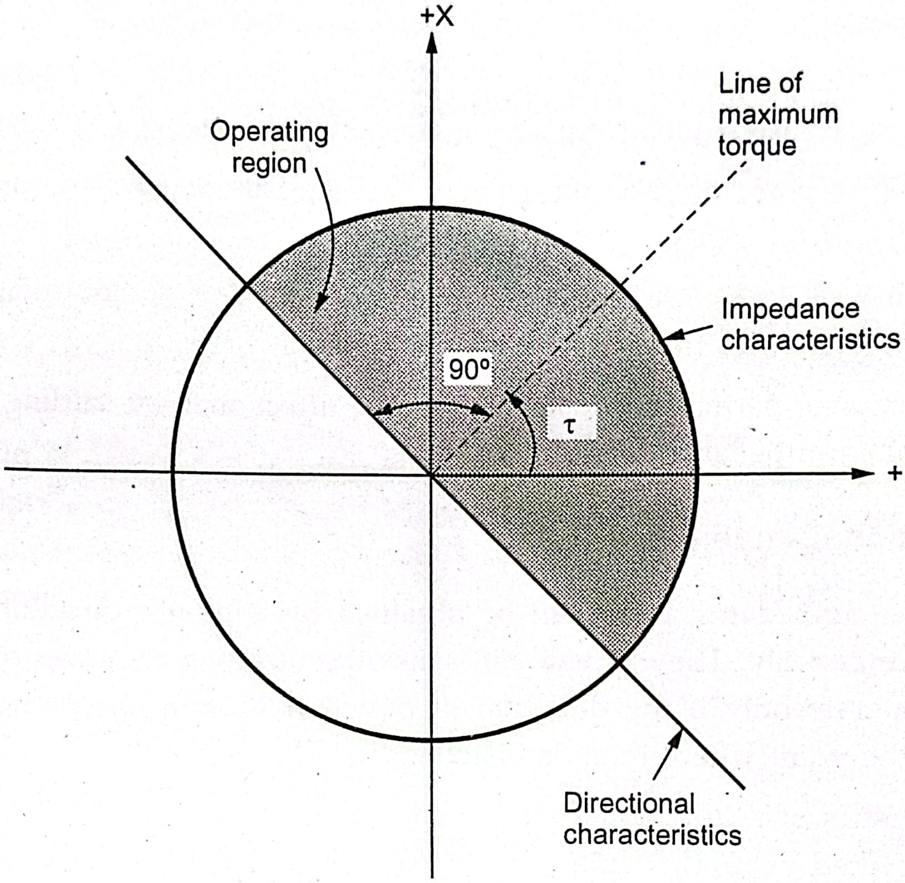

+X
Line of maximum torque
Operating region
Impedance characteristics
90°
τ
+R
Directional characteristics

Fig. 2.11.5 Directional impedance relay characteristics

Modified characteristics : By supplying additional voltage to the voltage coils of an impedance relay, the torque equation of the relay can be modified. The additional voltage supplied is proportional to the line current and is called current bias. The modified torque equation is,

$$T = K_1 I^2 - K_2 (V + K_3 I)^2$$

where $(V + K_3 I)$ = Voltage supplied to voltage coil

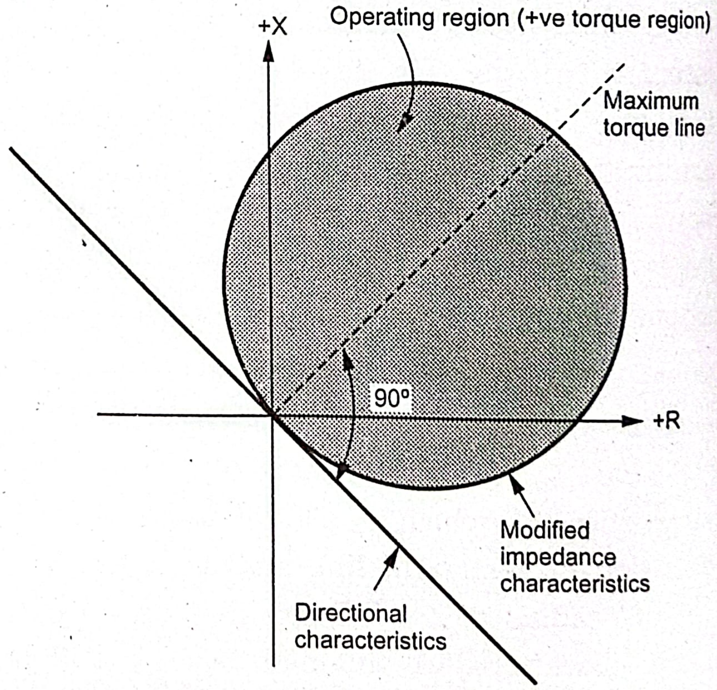

+X
Operating region (+ve torque region)
Maximum torque line
90°
+R
Modified impedance characteristics
Directional characteristics

Fig. 2.11.6 Modified directional impedance relay characteristics

Due to this additional current bias, the circle representing impedance characteristics on R-X diagram shifts. The radius of circle remains same as V/I but its centre gets shifted from origin. This is shown in the Fig. 2.11.6. By controlling current bias, shift of the circle can be adjusted as per the requirement.

Review Questions

1. *Explain an impedance relay showing its characteristics on R-X diagram.*

   AU : Dec.-06, 11, 13, 14, 15, May-06, 08, 12, 17, 18, 22, Marks 6

2. *Derive the torque equation of impedance relay from universal torque equation.*

   AU : May-13, Dec.-16, Marks 4

3. *How directional feature is provided to impedance relay ? Explain with the help of characteristics.*

2.12 Reactance Relay

AU : May-06,07,12,13,22, Dec.-08,11,15,16

In this relay the operating torque is obtained by current while the restraining torque due to a current-voltage directional relay. The overcurrent element develops the positive torque and directional unit produces negative torque.

Thus the reactance relay is an overcurrent relay with the directional restraint.

The directional element is so designed that the maximum torque angle is 90 °.

2.12.1 Construction

The structure used for the reactance relay can be of induction cup type. It is a four pole structure. It has operating coil, polarizing coil and a restraining coil. The schematic arrangement of coils for the reactance relay is shown in the Fig. 2.12.1.

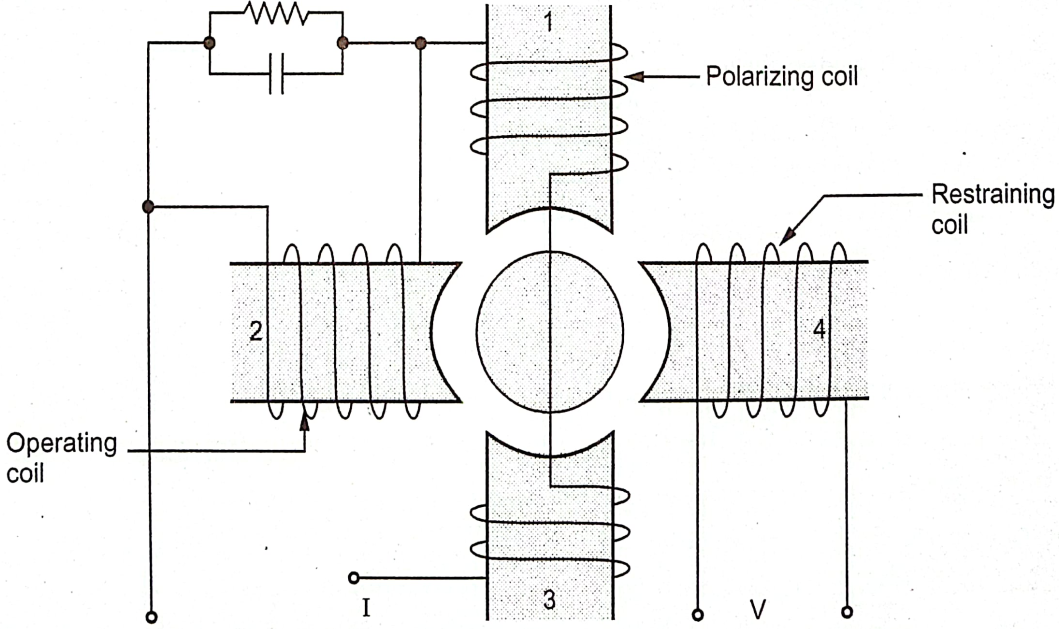


Fig. 2.12.1 Schematic arrangement of reactance relay

The current I flows from pole 1, through iron core stacking to lower pole 3. The winding on pole 4 is fed from voltage V. The operating torque is produced by interaction of fluxes due to the windings carrying current coils i.e. interaction of fluxes produced by poles 1, 2 and 3. While the restraining torque is developed due to interaction of fluxes due to the poles 1, 3 and 4. Hence the operating torque is proportional to the square of the current (I^2) while the restraining torque is proportional to the product of V and I (VI). The desired maximum torque angle is obtained with the help of RC circuit, shown in the Fig. 2.12.1.

2.12.2 Torque Equation

The driving torque is proportional to the square of the current while the restraining torque is proportional to the product of V and I.

Hence the net torque neglecting the effect of spring is given by,

$$T = K_1 I^2 - K_2 V I \cos(\theta - \tau)$$

At the balance point net torque is zero,

$$\therefore \quad 0 = K_1 I^2 - K_2 V I \cos(\theta - \tau) \quad \text{i.e.} \quad K_1 I^2 = K_2 V I \cos(\theta - \tau)$$

$$\therefore \quad K_1 = K_2 \frac{V}{I} \cos(\theta - \tau) \quad \text{i.e.} \quad K_1 = K_2 Z \cos(\theta - \tau)$$

Adding capacitor, the torque angle is adjusted as 90°,

$$\therefore \quad K_1 = K_2 Z \cos(\theta - 90^\circ) \quad \text{i.e.} \quad K_1 = K_2 Z \sin\theta$$

$$\therefore \quad Z \sin\theta = \frac{K_1}{K_2}$$

Consider an impedance triangle shown in the Fig. 2.12.2.

$$Z \sin\theta = X = \text{Reactance}$$

$$Z \cos\theta = R = \text{Resistance}$$

$$\therefore \quad \boxed{X = \frac{K_1}{K_2} = \text{Constant}}$$

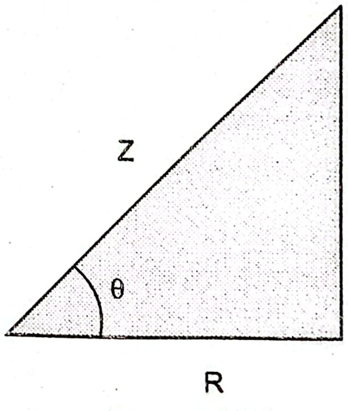


Fig. 2.12.2

Thus the relay operates on the reactance only. The constant X means a straight line parallel to X-axis on R-X diagram. For the operation of the relay, the reactance seen by the relay should be smaller than the reactance for which the relay is designed.

2.12.3 Operating Characteristics

The operating characteristics of such relay is a straight line parallel to the X-axis i.e R-axis on R-X diagram. All the impedance vectors have their tips lying on the straight line representing constant reactance. The resistance component of the impedance has no effect on the operation of the relay. It responds only to the reactance component of the impedance. The characteristics is shown in the Fig. 2.12.3.

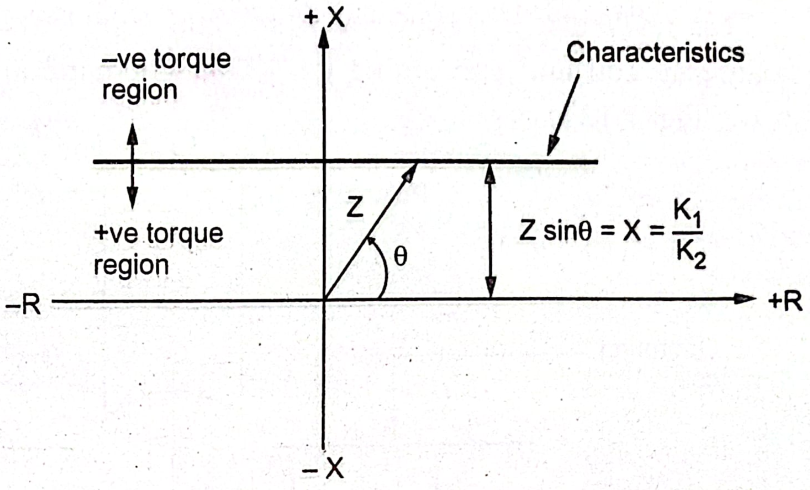


Fig. 2.12.3 Operating characteristics of reactance relay

The relay will operate for all the impedances whose heads lie below the operating characteristics, whether below or above the R-axis.

2.12.4 Disadvantages

This relay as can be seen from the characteristics is a nondirectional relay. This will not be able discriminate when used on transmission line, whether the fault has taken place in the section where relay is located or it has taken place in the adjoining section. It is not possible to use a directional relay of the type used with basic impedance relay because in that case the relay will operate even under normal load conditions if the system is operating at or near unity p.f. conditions. The reactance relay with directional feature is called mho relay or admittance relay.

Review Questions

1. *Explain a reactance relay showing its characteristics on R-X diagram.*

   AU : Dec.-08, 11, 15, May-06, 07, 12, 22, Marks 6

2. *Derive the torque equation of reactance relay from universal torque equation.*

   AU : May-13, Dec.-16, Marks 4

2.13 Mho Relay or Admittance Relay

AU : May-06,12,13,22, Dec.-07,11,12,13,15,16

In the impedance relay a separate unit is required to make it directional while the same unit cannot be used to make a reactance relay with directional feature. The mho relay is made inherently directional by adding a voltage winding called polarizing winding. This relay works on the measurement of admittance Y ∠ θ. This relay is also called angle impedance relay.

2.13.1 Construction

This relay also uses an induction cup type structure. It also has an operating coil, polarizing coil and restraining coil. The schematic arrangement of all the coils is shown in the Fig. 2.13.1.

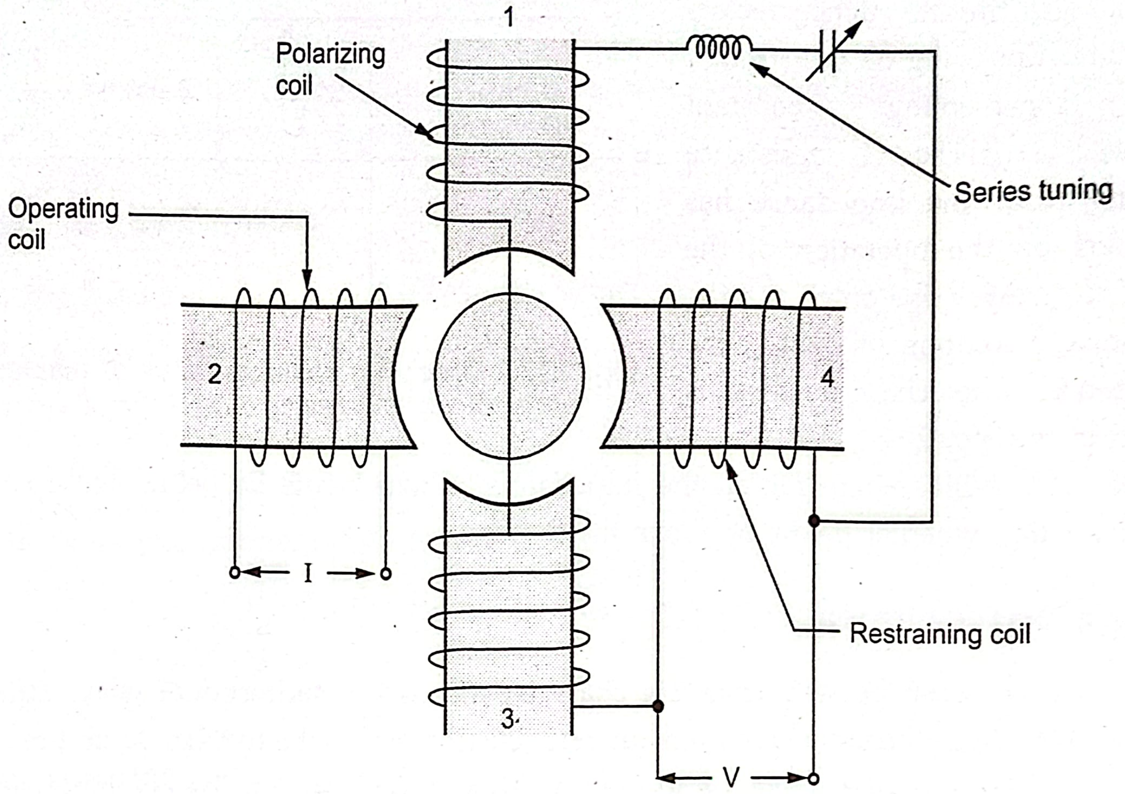


Fig. 2.13.1 Schematic arrangement of admittance relay

In this relay the operating torque is obtained by V and I element while the restraining torque is obtained by a voltage element. Thus an admittance relay is a voltage restrained directional relay.

The operating torque is produced by the interaction of the fluxes due to the windings carried by the poles 1, 2 and 3. While the restraining torque is produced by the interaction of the fluxes due to the windings carried by the poles 1, 3 and 4.

Thus the restraining torque is proportional to the square of the voltage (V^2) while the operating torque is proportional to the product of voltage and current (VI). The torque angle is adjusted using series tuning circuit.

2.13.2 Torque Equation

The operating torque is proportional to VI while restraining torque is proportional to V^2. Hence net torque is given by,

$$T = K_1 V.I \cos(\theta - \tau) - K_2 V^2 - K_3$$

where K_3 = Control spring effect

Generally control spring effect is neglected ($K_3 = 0$).

And at balance net torque is also zero.

$$\therefore \quad 0 = K_1 \, V \, I \cos(\theta - \tau) - K_2 \, V^2$$

$$\therefore \quad K_1 \, V \, I \cos(\theta - \tau) = K_2 \, V^2$$

$$\therefore \quad K_1 \cos(\theta - \tau) = K_2 \frac{V^2}{VI} \quad \text{i.e.} \quad K_1 \cos(\theta - \tau) = K_2 \frac{V}{I}$$

$$\therefore \quad \boxed{Z^2 = \frac{K_1}{K_2} \cos(\theta - \tau)}$$

This is the equation of a circle having diameter K_1/K_2 passing through origin. And this constant K_1/K_2 is the ohmic setting of this relay.

2.13.3 Operating Characteristics

As seen from the torque equation, the characteristics of this relay is a circle passing through origin with diameter as K_1/K_2.

Let $\frac{K_1}{K_2} = Z_R$ = Ohmic setting of relay = Diameter

The circle is shown in the Fig. 2.13.2.

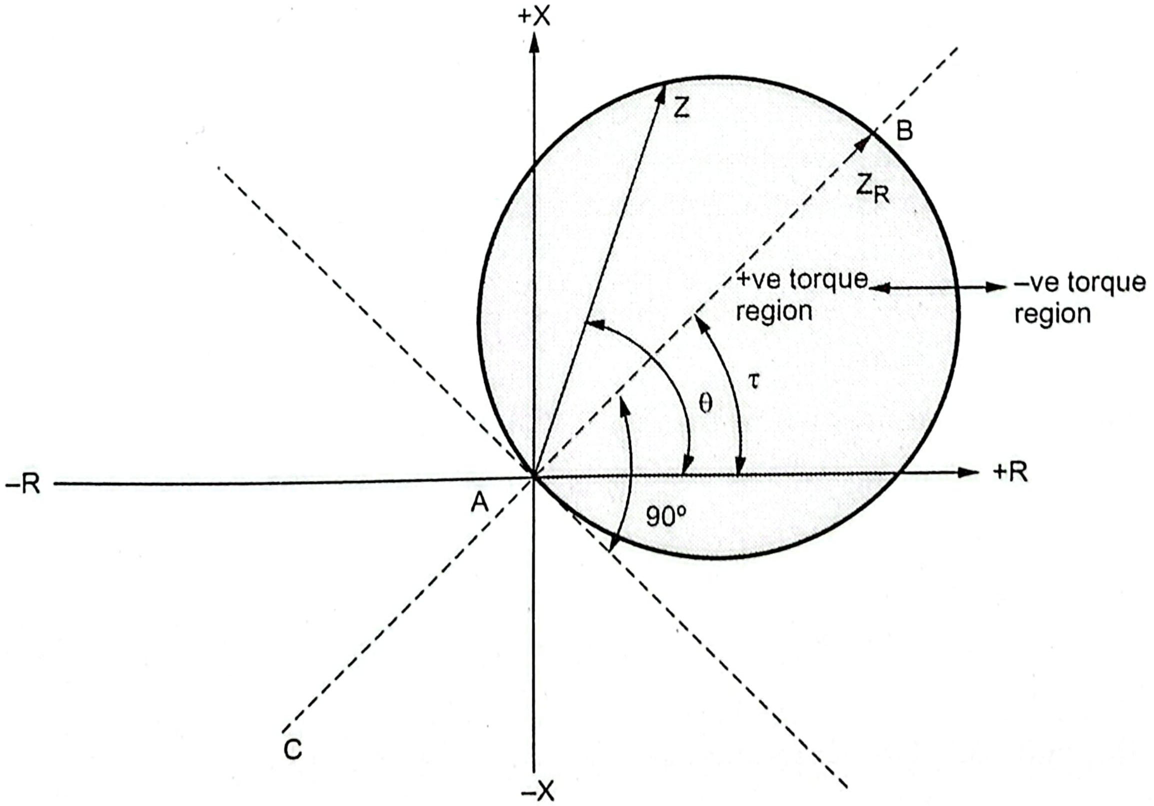


Fig. 2.13.2 Operating characteristics of mho relay

The relay operates when the impedance seen by the relay falls within this circle. Consider two lines AB and AC with mho relay located at the point A. The relay will operate for the faults occurring in the section AB only and not for the faults occurring in the section AC. This shows that this relay is inherently directional without any additional directional unit required.

The angle τ can be adjusted to be 45 °, 60 °, 75 ° and so on. This angle is maximum torque angle. The setting of 45 ° is used for high voltage (33 or 11 kV) distribution lines, the setting of 60 ° is used for 66 or 132 kV lines while the setting of 75 ° is used for 275 and 400 kV lines.

Example 2.13.1 *On a R-X diagram show a line having an impedance of 3 + j 4 Ω. On the same diagram show the operating characteristics of,*

1. Impedance relay 2. Reactance relay 3. Mho relay

Assume that these relays are adjusted to just operate for a zero impedance short circuit at the end of the line section.

If an arcing short circuit fault having an arc impedance of 1 + j0 Ω occurs anywhere on the line, find for each type of distance relay, the maximum portion of the line that can be protected.

Solution : The line OA is the impedance vector with impedance 3 + j 4 Ω.

$$OB = 3$$

$$BA = 4$$

The circle with O as a centre and OA as radius represents the characteristics of an impedance relay.

The line parallel to the resistance axis at a distance of 4, passing through point A, corresponding to reactance of the impedance given, represents the characteristics of a reactance relay.

Draw the circle with OA as the diameter, passing through O and A represents characteristics of mho relay.

The characteristics are shown in the Fig. 2.13.3. (See Fig. 2.13.3 on next page).

The impedance of arcing fault is 1 + j 0, is represented by OD.

The line parallel to the OA is drawn from point D, cutting the mho circle at point F and cutting the impedance circle at point E.

Draw line FN parallel to R-axis to cut OA at N and draw EM parallel to R-axis to cut OA at M.

Then the ratio ON/OA represents the line protected by mho relay.

$$\therefore \quad \frac{ON}{OA} \times 100 = \text{\% of line protected by mho relay} = \frac{4}{5} \times 100 = 80 \ \%$$

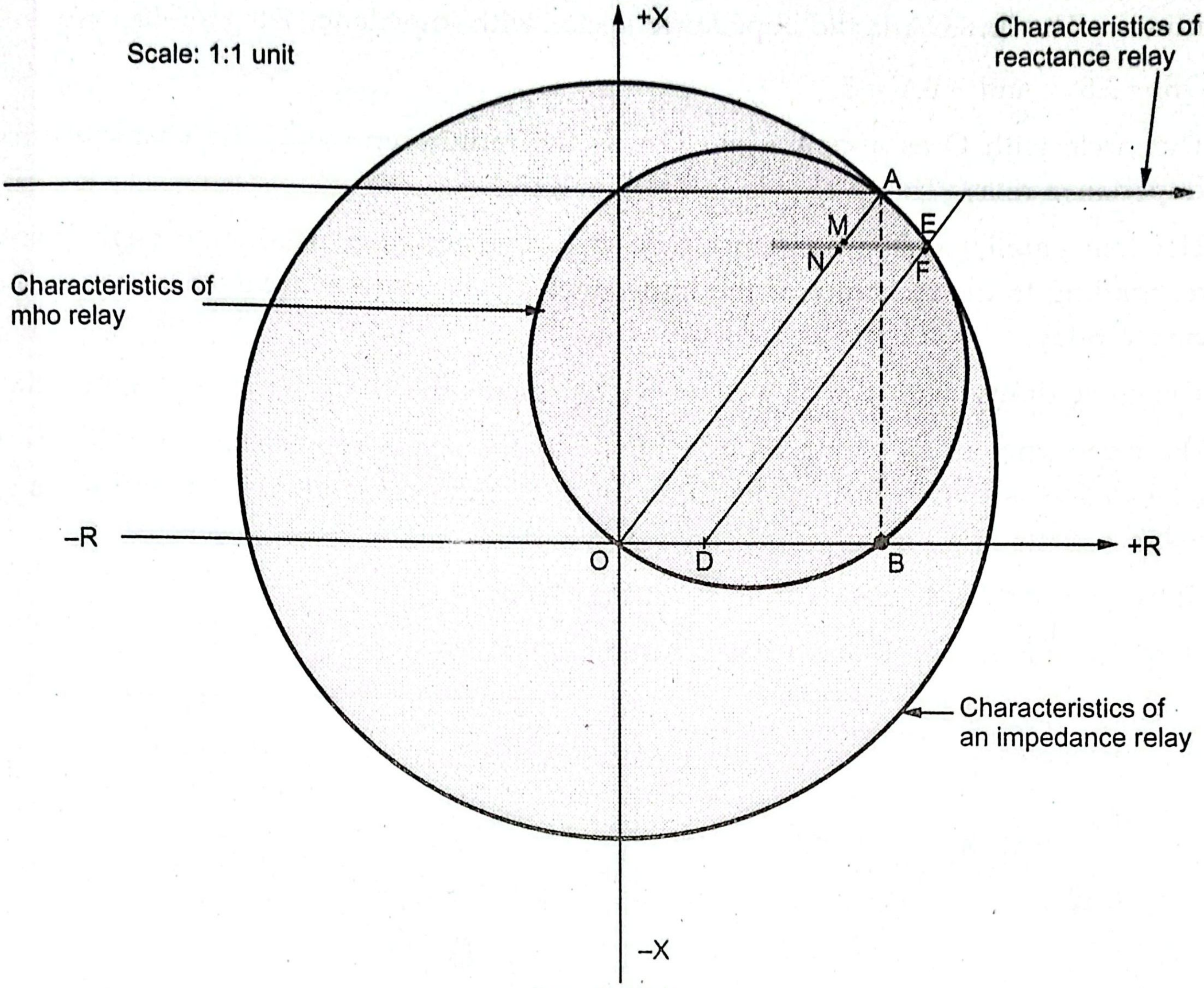

+X
Scale: 1:1 unit
Characteristics of reactance relay
A
M
E
N
F
Characteristics of mho relay
–R
O
D
B
+R
Characteristics of an impedance relay
–X

Fig. 2.13.3

While the ratio OM/OA represents the line protected by impedance relay.

$$\therefore \quad \frac{OM}{OA} \times 100 = \% \text{ of line protected by impedance relay} = \frac{4.25}{5} \times 100 = 85\ \%$$

Now reactance relay is unaffected by the presence of the arc resistance and hence even with the arc present the % of line protected by the reactance relay is 100 %.

Example 2.13.2 *A line section has an impedance of 2.8 + j 5 ohms. Show this on R-X diagram as impedance vector. If the relay is adjusted to just operate for a zero impedance short circuit at the end of the line section, show on the R-X diagram the operating characteristics of : i) An impedance relay ii) A reactance relay iii) A mho relay used for the purpose. Assume that the centre of the mho relay operating characteristics lies on the line impedance vector.*

If the arcing short circuit occurs having an impedance of 1.5 + j 0 ohms anywhere along the line, find for each type of distance relay the maximum portion of the line that can be protected.

Solution : The line OA is the impedance vector with impedance 2.8 + j 5 Ω.

OB = 2.8 and BA = 5

The circle with O as a centre and OA as the radius represents the characteristics of an **impedance relay**. This is shown in the Fig. 2.13.4.

The line parallel to the resistance axis at a distance of 5 passing through point A, corresponding to the reactance of the impedance given, represents the characteristics of a **reactance relay**.

The circle drawn with OA as a diameter represents the characteristics of **mho relay.**

The impedance of an arcing fault is 1.5 + j 0 Ω which is represented as OD. The line parallel to OA is drawn from point D, cutting the mho circle at point F and cutting an impedance circle at point E.

Draw line parallel to R-axis from F cutting OA at N.

Draw line parallel to R-axis from E cutting OA at M.

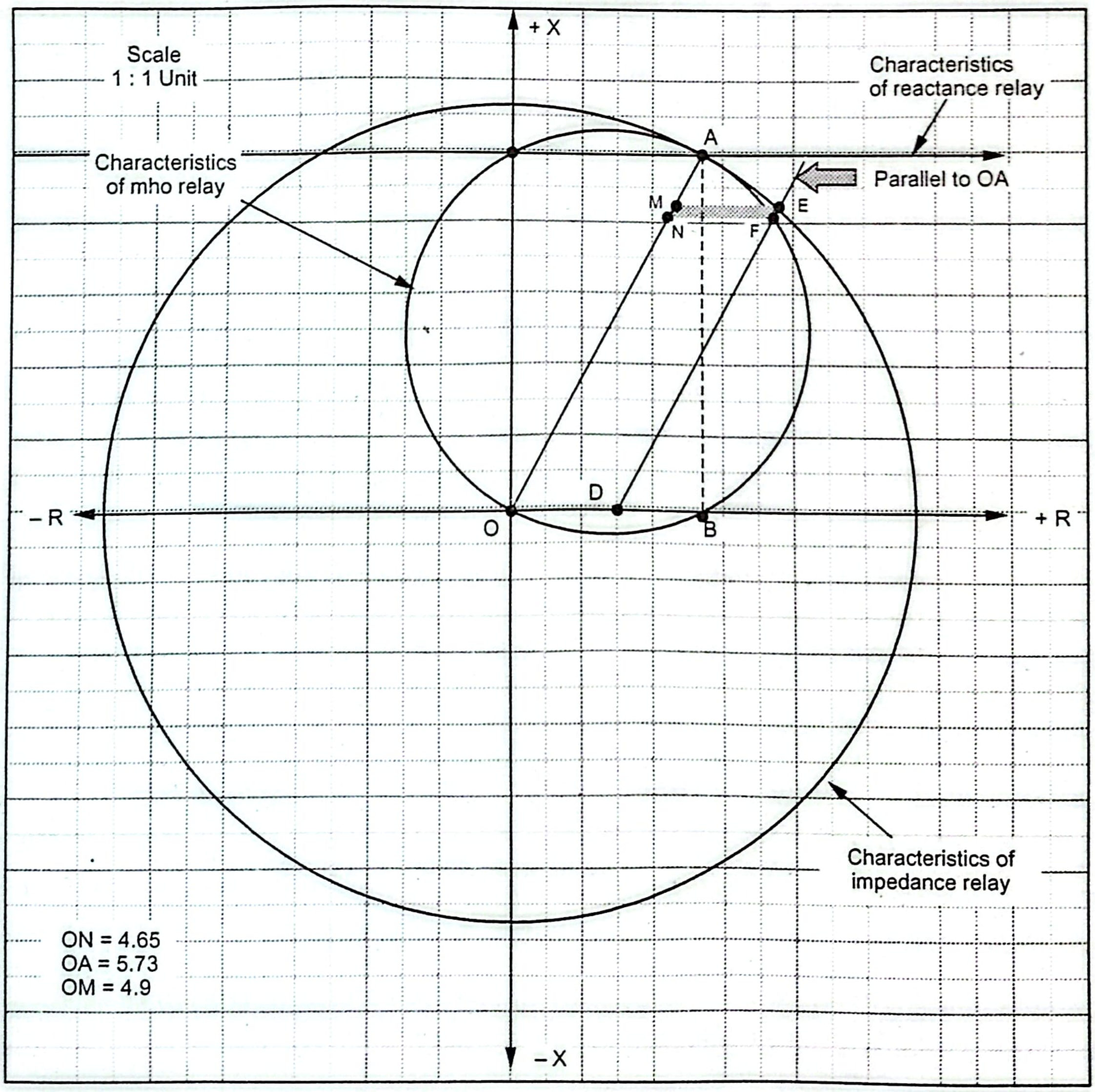

+X
Scale
1 : 1 Unit
Characteristics
of reactance relay
A
Characteristics
of mho relay
Parallel to OA
M
E
N
F
D
– R
O
B
+ R
Characteristics of
impedance relay
ON = 4.65
OA = 5.73
OM = 4.9
– X

Fig. 2.13.4

The ratio of ON to OA represents the line protected by the mho relay.

$$\therefore \quad \frac{ON}{OA} \times 100 = \frac{4.65}{5.73} \times 100$$

$$= \mathbf{81.14\ \%} \qquad \text{... Line protected by mho relay}$$

The ratio OM to OA represents the line protected by an impedance relay.

$$\therefore \quad \frac{OM}{OA} \times 100 = \frac{4.9}{5.73} \times 100$$

$$= \mathbf{85.5\ \%} \qquad \text{... Line protected by impedance relay}$$

The reactance relay is unaffected by the presence of the arc resistance and hence even with the arc present the % line protected by the reactance relay is **100 %.**

Review Questions

1. *Explain mho relay showing its characteristics on R-X diagram.*

AU : Dec.-07, 11, 12, 13, 15, May-06, 12, 22, Marks 6

2. *Derive the torque equation of mho relay from universal torque equation.*

AU : Dec.-07,16, May-13, Marks 4

3. *A line section has an impedance of 2.8 + j 5 Ω. Show this on R-X diagram, as impedance vector. If the relay is adjusted to operate for a zero impedance short circuit at the end of the line section, show on the same R-X diagram the characteristics of,*

   1. Impedance relay 2. Reactance relay 3. Mho relay

   Assume that centre of mho relay characteristics lies on an impedance vector. If the arching fault occurs with an impedance of 1.5 + j 0 Ω anywhere along the line, find for each type of distance relay the maximum portion of the line that can be protected.

   (Ans. : 82 %, 100 % and 85 %)

2.14 Classification of Distance Relays

We have seen that the distance relay basically measures ohmic values and operates when the impedance is below the preset value. The distance relays are classified as,

1. **Definite distance relays :** These can be of impedance type, reactance type or mho type. This operates instantaneously for the faults upto certain predetermined distance from the relay.

2. **Distance time relays :** These can be also of impedance type, reactance type or mho type. In these relays the time of operation is proportional to the distance of the fault from the point where relay is installed. The fault nearer to the relay operates it faster than for the faults farther away from the relay.

Let us discuss the construction and operation of these two types of distance relays.

2.14.1 Definite Distance Type Impedance Relay

The construction of this relay can be balanced beam type or induction disc type. The balanced beam type construction of definite distance impedance relay is shown in the Fig. 2.14.1.

It consists of a balanced beam pivoted at the central point C. The beam carries the armatures of the two electromagnets. The two electromagnets are energized by a current from C.T. and voltage from P.T., which are located in the circuit to be protected. The voltage coil acts as restraining coil while the current coil acts as operating coil. The beam also carries the moving contacts which can bridge the two fixed contacts of a trip circuit when the relay operates.

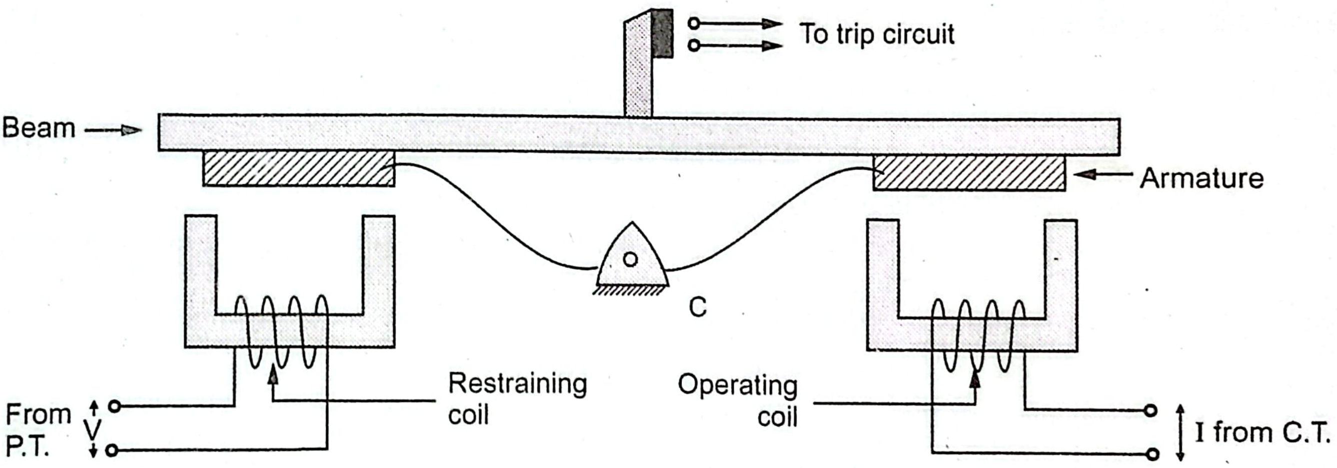


Fig. 2.14.1 Definite distance type impedance relay

Operation : The torque produced by voltage coil is proportional to square of the voltage ($K_1 V^2$) while the torque produced by current coil is proportional to the square of the current ($K_2 I^2$). Under normal operating conditions, the torque produced by voltage coil is more than the torque produced by the current coil. Thus restraining torque is more than the operating torque and hence the relay is inoperative. On the occurrence of any fault, the voltage of system decreases and current increases. Thus the ratio V/I which is impedance also decreases. It falls below its preset value. The torque produced by current coil becomes greater than the torque produced by the voltage coil. Hence beam experiences a pull on the current coil side. As the beam tilts, the moving contacts of beam bridges the fixed contacts of the trip circuit. This operates the trip circuit and opens the circuit breaker.

Torque Equation : The torque by voltage coil is proportional to V^2 while that by current coil is I^2.

The relay will operate when torque produced by voltage coil is less than that produced by current coil. So we can write,

$$K_1 V^2 < K_2 I^2 \qquad \text{... Relay operates}$$

where K_1, K_2 = Constants

$$\therefore \quad \frac{V^2}{I^2} < \frac{K_2}{K_1} \quad \text{i.e.} \quad \frac{V}{I} < \sqrt{\frac{K_2}{K_1}} \quad \text{i.e.} \quad Z < \sqrt{\frac{K_2}{K_1}}$$

So for impedance value less than $\sqrt{K_2/K_1}$, the relay operates.

The constants K_1 and K_2 are dependent on the ampere turns of the two electromagnets. By providing tappings on the coils, K_1 and K_2 can be changed and hence any preset value for the impedance can be adjusted as per the requirement.

Characteristics : The Fig. 2.14.2 shows the characteristics of the definite distance type impedance relay. The Y-axis represents time for operation while the X-axis represents distance which is measured interms of impedance between fault position and the point where relay is installed.

For the entire length AB of the line, the time of operation remains constant, irrespective of distance. But if fault occurs in the section of line which is not protected, the operating time becomes suddenly infinite as shown in the Fig. 2.14.2. Towards end of the protected zone, the curve rises gradually.

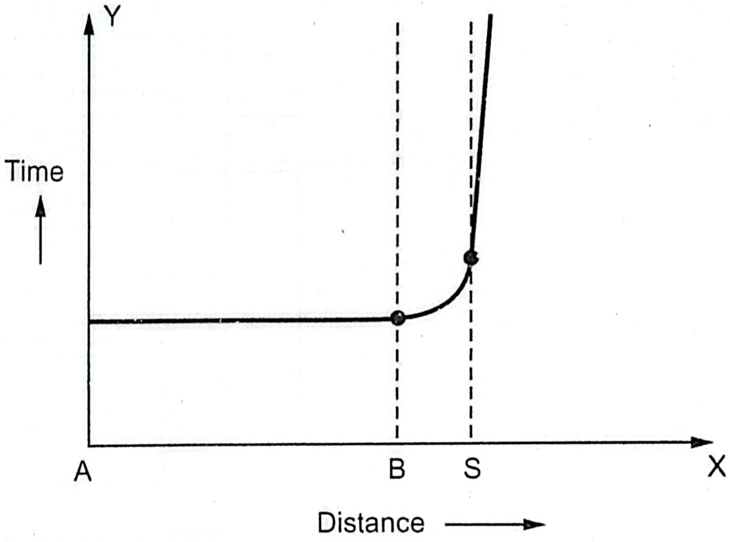


Fig. 2.14.2 Characteristics of definite distance impedance relay

Its advantages are,

1. Superior to the time graded overcurrent relay.
2. Number of feeders in series which can be protected is unlimited as the relay time is constant.

The one limitation of these relays is the absence of back up protection.

2.14.2 Distance Time Impedance Relay

This relay adjusts automatically, its time or operation corresponding to the distance of the fault from the relay.

$$\text{Operating time} \propto Z \propto \text{Distance}$$

The Fig. 2.14.3 shows the schematic arrangement of distance time impedance relay.

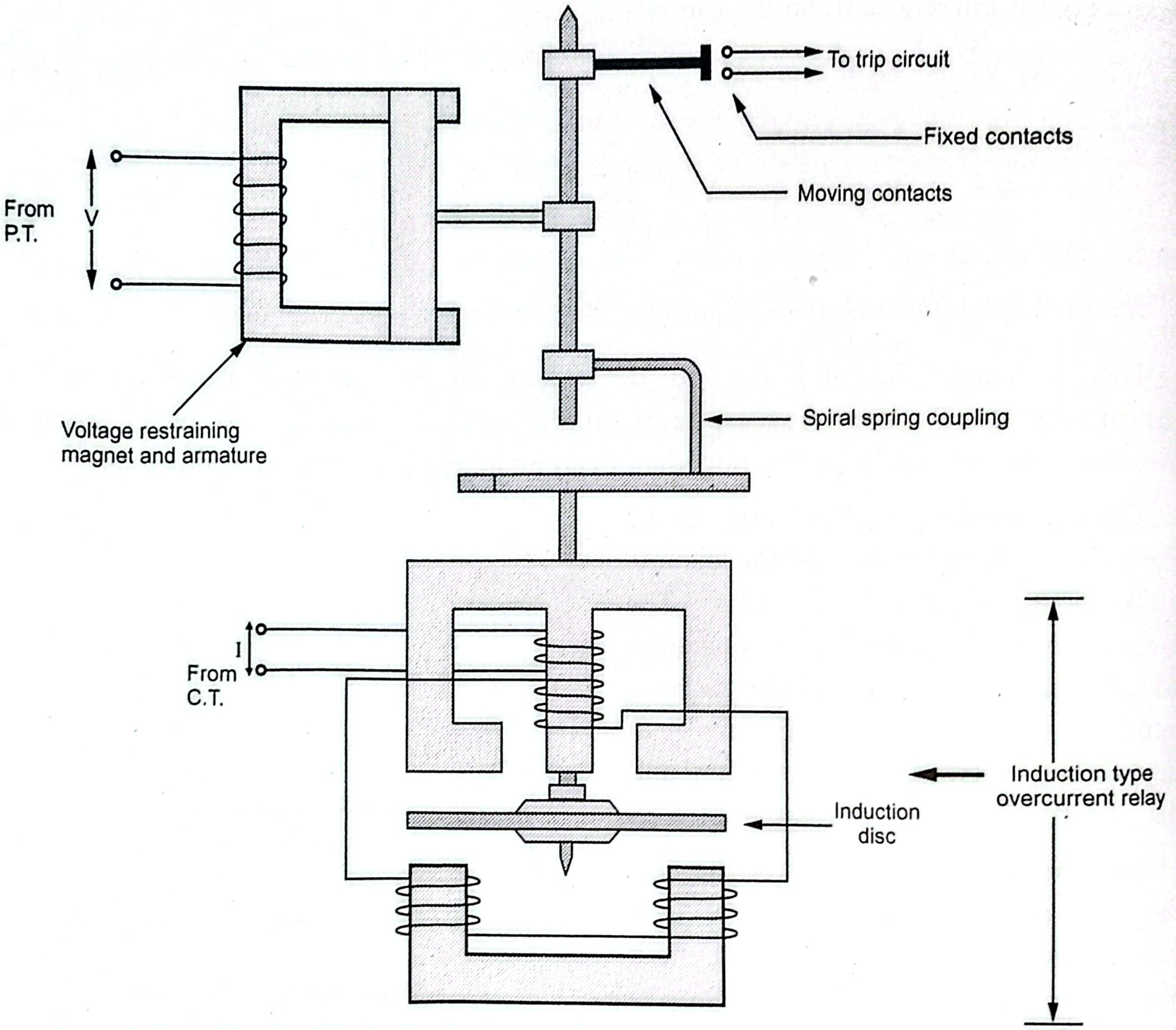

To trip circuit
Fixed contacts
Moving contacts
From P.T.
V
Voltage restraining magnet and armature
Spiral spring coupling
I
From C.T.
Induction disc
Induction type overcurrent relay

Fig. 2.14.3 Distance time impedance relay

It consists of an induction type overcurrent relay unit which is a current driven element. The spindle which is carrying the disc of the element is connected to a second spindle with the help of spiral spring coupling. This second spindle carries moving contacts which is nothing but a bridging piece which can bridge the trip contacts when relay operates. The trip contacts are normally open and spindle is held in this position by an armature held against the pole face of an electromagnet. This electromagnet is energized by the voltage of the circuit to be protected.

Operation : Under normal conditions, the force exerted by voltage restraining magnet is more than that produced by an overcurrent induction element. Thus the trip contacts remain open and the relay is inoperative.

When the fault occurs, the induction disc starts rotating. The speed of the disc is proportional to the operating current, neglecting the spring effect. Hence the time which the disc requires to turn through the given angle varies inversely with current. As the disc rotates, spiral spring is wound. This exerts a force on armature so as to pull it away from the voltage restrained magnet. The disc continues to rotate till the tension of the spring is sufficient to overcome the restraining force produced by voltage restraining magnet on the armature. Immediately the moving contacts bridge the fixed contacts of tripping circuit. This opens the circuit breaker to isolate the faulty section.

The angle through which the disc must rotate to close the trip contacts depends on the pull required by armature which is restrained by voltage restraining magnet. This pull is thus proportional to the voltage of system. Greater this pull, greater will be travel of the disc. So travel for the disc is proportional to the voltage V. But the time which disc takes to rotate through certain required angle varies inversely with current (1/I). Thus effectively,

$$\text{Time of operation of relay} \propto \frac{V}{I} \propto Z \propto \text{Distance}$$

In actual practice the pull on armature is proportional to the V^2 while the torque on disc is proportional to the I^2. Hence the time distance characteristics of this relay is nonlinear in nature, as shown in the Fig. 2.14.4. The exact curve is shown dotted while the assumed line is shown thick. The minimum operating time for the relay is generally 0.2 seconds.

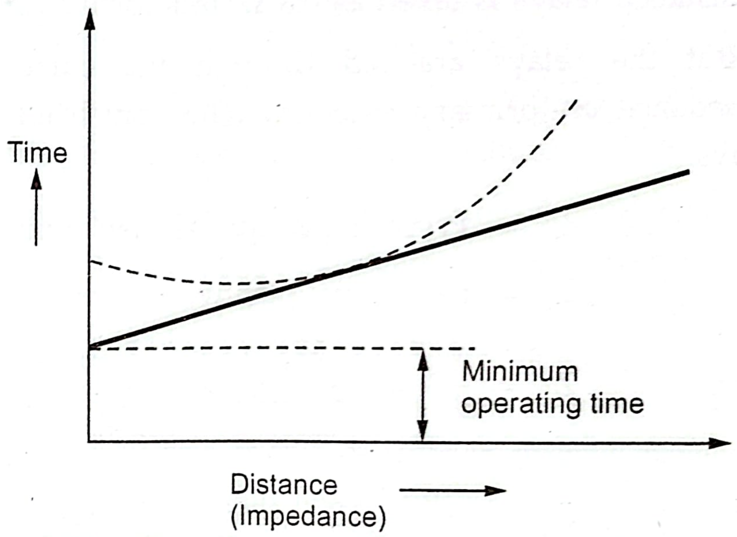


Fig. 2.14.4 Time-distance characteristics of distance time impedance relay

2.14.3 Applications and Advantages of Distance Relays

The various advantages of the distance relays are,

1. Gives faster operation. 2. Simpler to co-ordinate.

3. Less effect of fault levels and fault current magnitudes.

4. Permits high line loading.

5. With the need at readjustments, permanent settings can be done.

Thus the distance relays are used for providing the primary i.e. main protection and backup protection for a.c. transmission and distribution lines against the following faults,

1. Three phase faults 2. Phase to phase faults 3. Phase to earth faults.

Review Questions

1. *Explain the construction and working of,*
   - *i) Definite distance type impedance relay*
   - *ii) Distance time impedance relay*
2. *State the advantages and applications of distance relays.*

2.15 Setting of Distance Relays

AU : May-06, Dec.-12

The positive phase sequence impedance exists between the location of relay and the location of fault beyond which relay operation should stop. The setting of distance relays is done based on this positive phase sequence impedance.

The corresponding distance upto which the relay is operative is called the **reach** of the relay. In practice, the value of the positive sequence impedance used for the setting of distance relays is taken as 0.8 Ω/mile or 0.5 Ω/km.

But the relays are fed through the current and potential transformers. Hence impedance on primary side must be converted to secondary, for setting the distance relays.

Let Z_p = Primary positive sequence impedance

Z_s = Secondary positive sequence impedance

Then,

$$Z_s = \frac{V_s}{I_s} = \frac{V_p}{\text{P. T. ratio}} \times \frac{\text{C. T. ratio}}{I_p}$$

But

$$Z_p = \frac{V_p}{I_p} = 0.8\ \Omega/\text{mile or } 0.5\ \Omega/\text{km}$$

$$\text{C.T. ratio} = \frac{\text{H. V. phase current}}{\text{Relay phase current}}$$

$$\text{P.T. ratio} = \frac{\text{H. V. phase to phase voltage}}{\text{Relay phase to phase voltage}}$$

$$\therefore \quad \boxed{Z_s = Z_p \times \frac{\text{C. T. ratio}}{\text{P. T. ratio}}}$$

Hence for 100 mile, 132 kV line with 500/5 star connected C.T.s with P.T. ratio of 132 kV/115 V, the secondary impedance is given by,

$$Z_s = (0.8\ \Omega/\text{mile}) \times 100 \text{ miles} \times \frac{500}{5} \times \frac{115}{132 \times 10^3} = 6.96 \approx 7\ \Omega$$

Practically the first zone of the distance relays is adjusted to reach 75 % of the length of the two ended line.

$$\therefore \qquad Z_s \text{ for 75 \% reach of length} = 0.75 \times 7 = 5.25\ \Omega$$

This value of the secondary positive sequence impedance must fall within the relay setting. This is how, the setting of distance relays is achieved.

Review Question

1. *Discuss the setting of distance relays.* **AU : May-06, Dec.-12, Marks 6**

2.16 Differential Relays

AU : Dec.-05,06,08, May-12,18

In the overcurrent relays, a current is sensed but such relays are not very sensitive as these relays cannot distinguish between heavy loads and minor fault conditions. In such cases, differential relays can be used.

A **differential relay** is defined as the relay that operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined value.

Thus a current differential relay operates on the result of comparison between the phase angle and magnitudes of the currents entering and leaving the system to be protected. Under normal conditions, the two currents are equal in phase and magnitude hence relay is inoperative. But under fault conditions, this condition no longer exists. The relay is connected in such a manner that the difference between current entering and current leaving flows through the operating coil. If this difference current exceeds a preset value then the relay operates and opens the circuit breaker.

Almost any type of relay when connected in a certain way can be made to operate as a differential relay.

2.16.1 Types of Differential Relays

The various types of differential relays are,

1. Current differential relay
2. Biased beam relay or percentage differential relay
3. Voltage balance differential relay

2.16.1.1 Current Differential Relay

Most of the differential relays are of current differential type. Consider an over current relay connected in the circuit so as to operate as the current differential relay. This is shown in the Fig. 2.16.1.

Two current transformers are used having same ratio are connected on the either side of the section to be protected. The secondaries of current transformers are connected in series, so they carry induced currents in the same direction. Let current I is flowing through the primary of current transformers towards the external fault. As the current transformers are identical, the secondaries of current transformers will carry equal currents. Due to the connection of relay, no current will flow through the operating coil for the relay. Hence relay will remain inoperative. So relay cannot operate if there is an external fault.

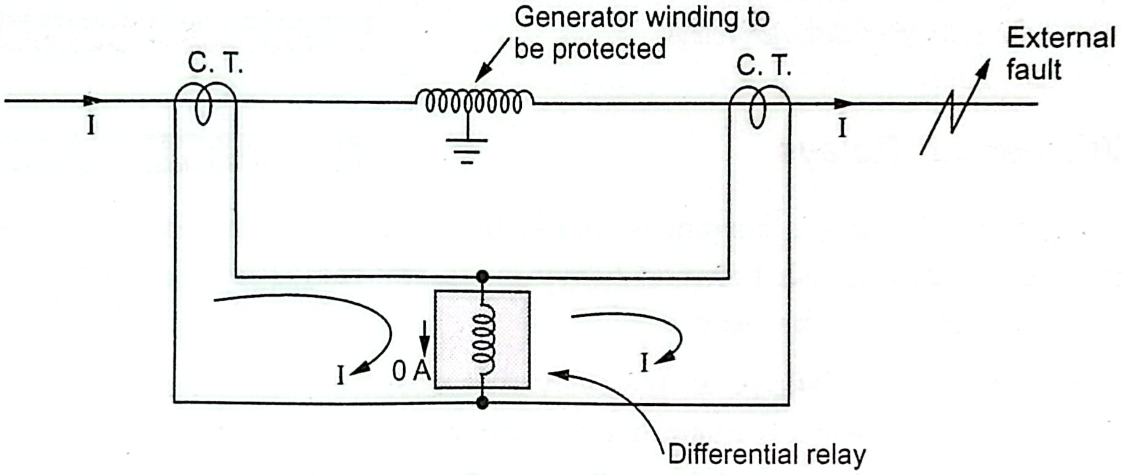


Fig. 2.16.1 Current differential relay

Consider now that an internal fault occurs at point A, as shown in the Fig. 2.16.2.

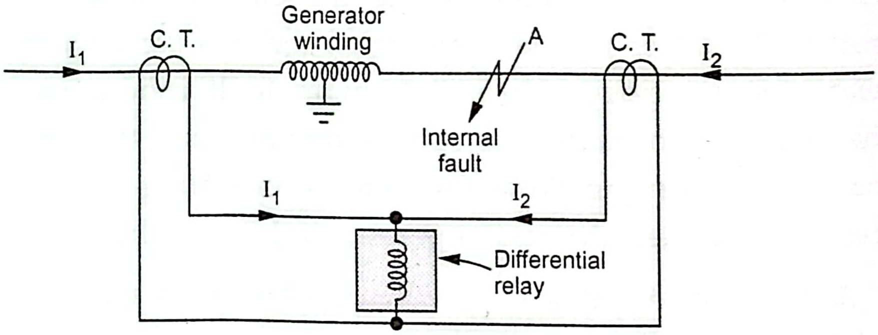


Fig. 2.16.2 Action of differential relay

The current flows through the fault from both sides. The two secondary currents through C.T.s are not equal. The current flowing through the relay coil is now $I_1 + I_2$. This high current causes the relay to operate.

It should be noted that the fault current need not always flow to the fault from both sides. A flow on one side only or even some current flowing out of one side while a large current entering the other side can cause differential relay to operate. Thus the amount of current flowing through a relay coil depends upon the way the fault is being fed.

This relay suffers from the following **disadvantages,**

1. The current transformers are connected through cables called pilot cables. The impedance of such pilot cables generally causes a slight difference between the currents at the ends of the section to be protected. A sensitive relay can operate to a very small difference in the two currents, though there is no fault existing.

2. The relay is likely to operate inaccurately with heavy through current flows. This is because the assumed identical current transformers may not have identical secondary currents due to the constructional errors and pilot cable impedances.
3. Under severe through fault conditions, the current transformers may saturate and cause unequal secondary currents. The difference between the currents may approach the pick value to cause the inaccurate operation for the relay.
4. Under heavy current flows, pilot cable capacitances may cause inaccurate operation of the relay.

All these disadvantages are overcome in biased beam relay.

2.16.1.2 Biased Beam Relay or Percentage Differential Relay

As the name suggests, this relay is designed to operate to the differential current in terms of its fractional relation with the actual current flowing through the protected circuit.

The Fig. 2.16.3 shows the arrangement of a biased beam relay.

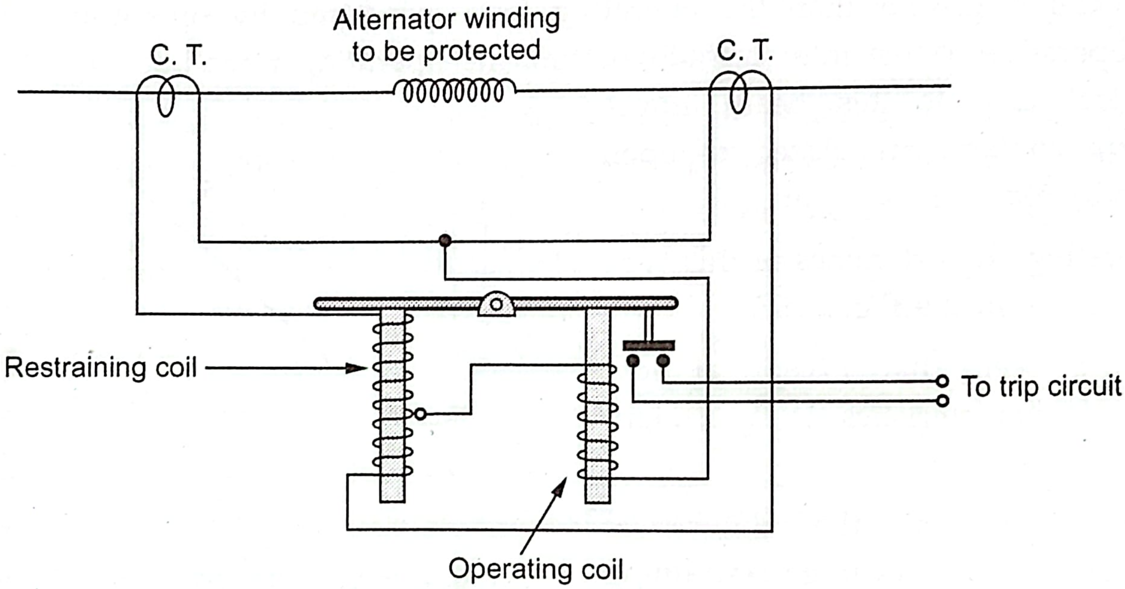

Alternator winding
to be protected
C. T.
C. T.
O
Restraining coil
To trip circuit
Operating coil

Fig. 2.16.3 Biased beam relay

The simple circuit connection of this type of relay is shown in the Fig. 2.16.4.

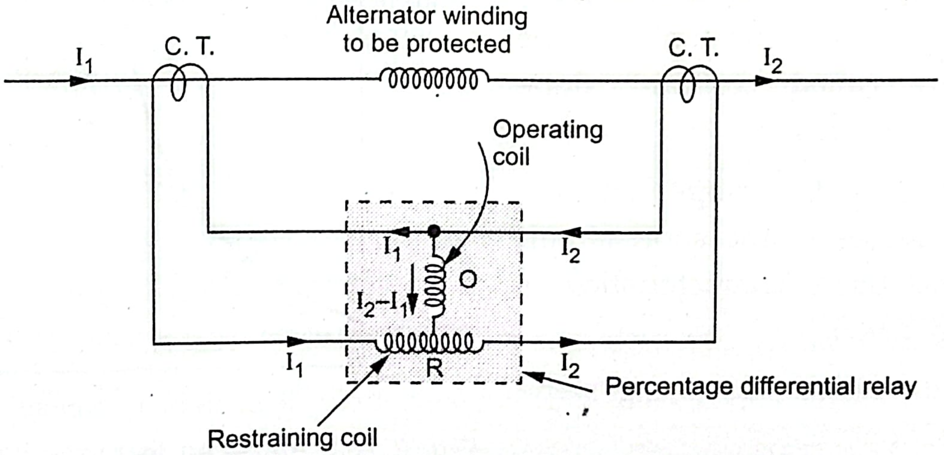

Alternator winding
to be protected
I_1
C. T.
C. T.
I_2
Operating coil
I_1
I_2
O
I_2-I_1
R
I_1
I_2
Percentage differential relay
Restraining coil

Fig. 2.16.4 Simple circuit of biased beam relay

The operating coil O of the relay carries a differential current $(I_2 - I_1)$ while the restraining coil R carries the current proportional to $\left(\frac{I_1 + I_2}{2}\right)$ as the operating coil is connected at the midpoint of the restraining coil. This can be explained as,

Let N = Total number of turns of restraining coil

So current I_1 flows through $\frac{N}{2}$ turns while current I_2 flows through $\frac{N}{2}$.

$$\therefore \text{ Effective ampere turns} = \frac{I_1 N}{2} + \frac{I_2 N}{2} = N\left(\frac{I_1 + I_2}{2}\right)$$

Thus it can be assumed that the current $\left(\frac{I_1 + I_2}{2}\right)$ flows through the entire N turns of the restraining coil.

Under normal and through load conditions, the bias force produced due to the restraining coil is greater than the operating force produced by operating coil hence relay is inoperative. When internal fault occurs, the operating force becomes more than the bias force. Due to this, beam moves and the trip contacts are closed to open then circuit breaker.

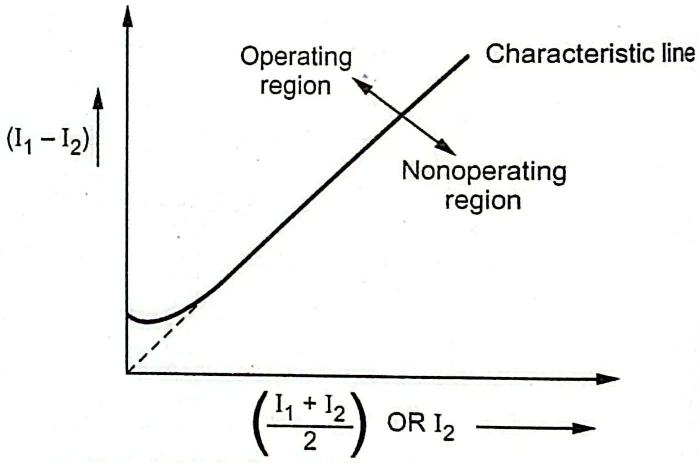


Fig. 2.16.5 Operating characteristics

The operating characteristics of this type of relay is shown in the Fig. 2.16.5.

It can be seen that except at low currents, the characteristics is a straight line.

Thus the ratio of the differential operating current to the average restraining current is a fixed percentage. Hence the relay name is percentage differential relay.

The relays with constant slope characteristics are called constant slope percentage differential relays.

In some relays, the slope of the characteristics increases as the short circuit current increases. Such characteristics is shown in the Fig. 2.16.6.

Such relays are called increasing slope percentage differential relays.

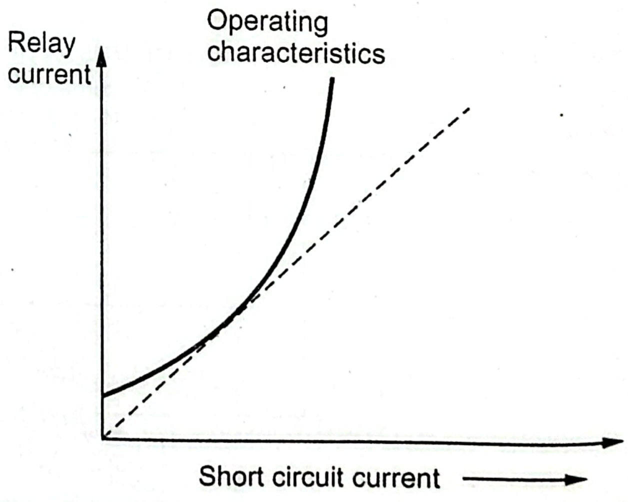


Fig. 2.16.6 Increase in slope characteristic

The important fact about increasing slope type relays is that their cost is more but require less accuracy in the performance of their current transformers. Constant slope type relays require good accuracy in the performance of the current transformers.

2.16.1.3 Voltage Balance Differential Relay

This is also called opposed voltage method. In this type, the over current relay is connected in series with the secondaries of the current transformers. This is shown in the Fig. 2.16.7.

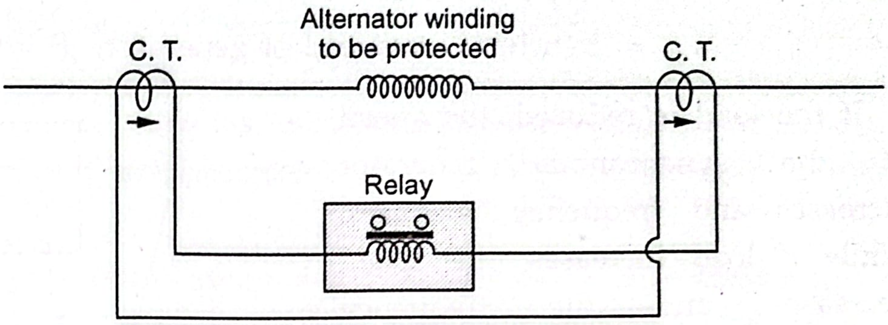


Fig. 2.16.7 Voltage balance differential relay

Under normal conditions, the current at the two ends of the section to be protected is same. Hence there is no voltage drop across the relay to cause the current to flow.

Under fault conditions, the currents in the two secondaries of current transformers are different. This causes a large voltage drop across the relay. Thus the voltage balance of the circuit gets disturbed. Hence large current flows through the relay due to which the relay operates to open the circuit breaker.

The disadvantages of voltage balance differential relay are :

1. For achieving the perfect balance between C.T. pairs, a special multigap transformer construction is required.
2. Under heavy current flows, capacitances of pilot cable wires may cause inaccurate operation of the relay.
3. The system is suitable for protection of lines having relatively short lengths.

All these disadvantages are eliminated in a translay relay.

Review Questions

1. *Explain the principle of percentage biased differential relay with necessary diagrams.*

   AU : May-12, Marks 8

2. *Explain the principle of operation of : i) Circulating current differential protection ii) Balanced voltage differential protection.*

   AU : Dec.-05, Marks 16

3. *With a neat sketch, explain the working of a current differential relay. State its disadvantages.*

   AU : Dec.-06, 08, May-18, Marks 8

2.17 Frequency Relay

AU : Dec.-10,14, May-14

The frequency of the induced e.m.f. is related to the speed of the synchronous generators by the relation,

$$f = \frac{N_s P}{120} \quad \text{where} \quad f = \text{Frequency}$$

N_S = Synchronous speed of generator, P = Number of poles

If the load is reduced, the speed of the synchronous generator increases and frequency increases. While if load increases, the speed decreases and the frequency decreases. Hence frequency relays are required if frequency changes from its normal value and are used in the generator protection and for load frequency control.

The frequency relays can be electromagnetic or static relays. These can be **under frequency** or **over frequency** relays.

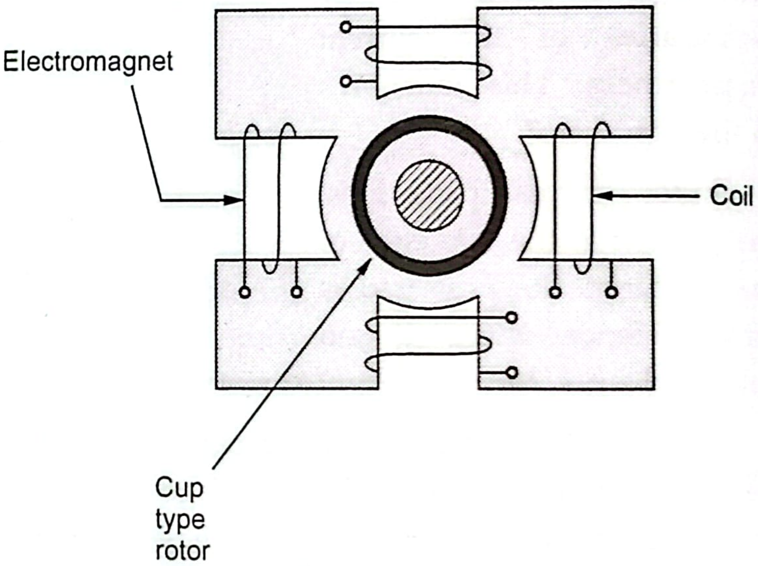


Fig. 2.17.1

Constructionally it consists of two pairs of coils and a cup type rotor as shown in the Fig. 2.17.1.

It uses a Ferraris measuring system. The frequency relays are connected to the secondary of voltage transformer. The two pairs of coils are connected in parallel to the supply voltage through the impedances.

Now impedances are functions of frequency. At normal frequency the impedances are tuned balancing each other. Thus no torque is experienced by the cup type rotor at normal rated frequency.

If frequency increases then there is unbalance in the impedances and torque say clockwise in nature is exerted on the rotor. This operates the relay if frequency increases beyond the setting. This is **over frequency relay.**

If frequency decreases then again there is unbalance in the impedances. But now torque exerted on the rotor is anticlockwise. This operates the relay if frequency decreases beyond the setting. This is **under frequency relay.**

By varying the position of sliding resistor the frequency setting can be adjusted. The pickup sensitivity can be controlled by adjusting the restraining spring.

Review Question

1. *Explain the construction and operation of frequency relay.* **AU : May-14, Dec.-10,14, Marks 8**

2.18 Negative Sequence Relays

AU : May-06,14,15,18,19, Dec.-13

The negative relays are also called phase unbalance relays because these relays provide protection against negative sequence component of unbalanced currents existing due to unbalanced loads or phase-phase faults. The unbalanced currents are dangerous from generators and motors point of view as these currents can cause overheating. Negative sequence relays are generally used to give protection to generators and motors against unbalanced currents.

A negative sequence relay has a filter circuit which is operative only for negative sequence components. Low order of over current also can cause dangerous situations hence a negative sequence relay has low current settings. The earth relay provides protection for phase to earth fault but not for phase to phase fault. A negative sequence relay provides protection against phase to phase faults which are responsible to produce negative sequence components.

The Fig. 2.18.1 shows the schematic arrangement of negative phase sequence relay.

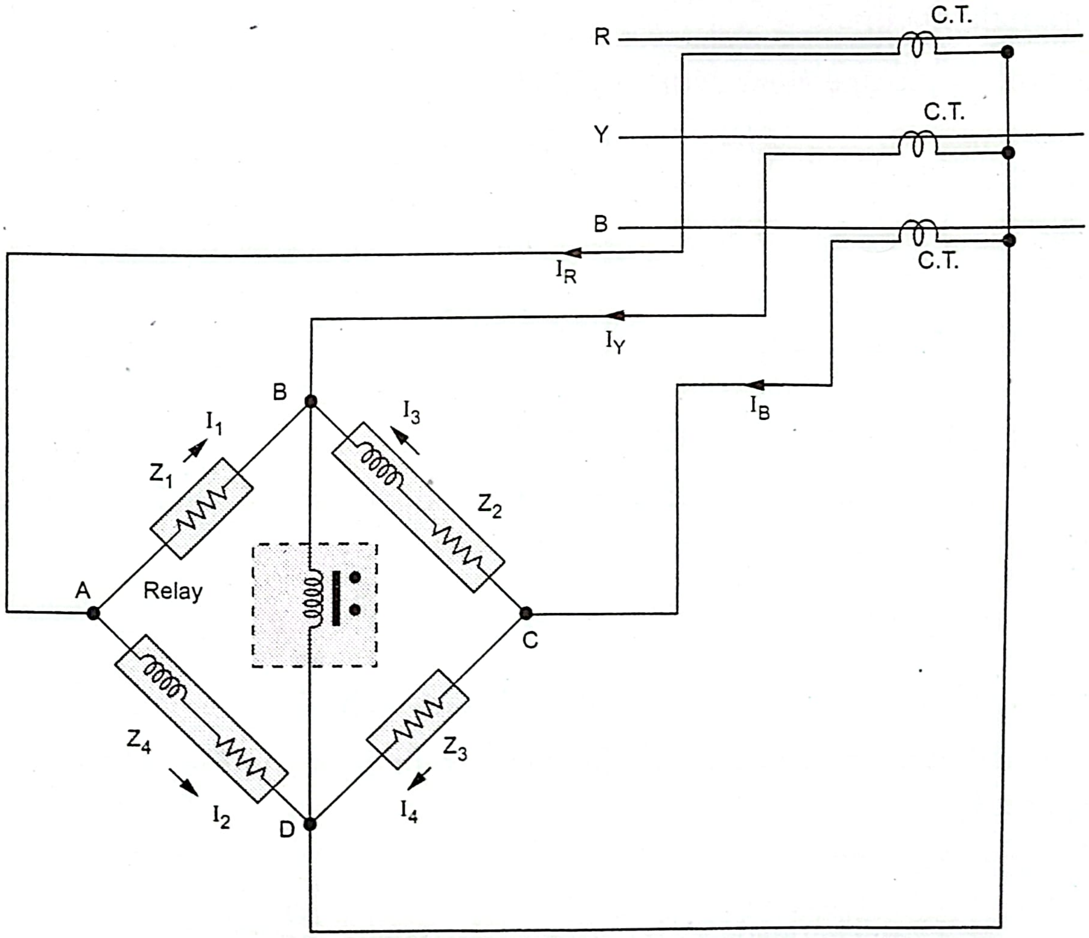


Fig. 2.18.1 Negative phase sequence relay

Basically it consists of a resistance bridge network. The magnitudes of the impedances of all the branches of the network are equal. The impedances Z_1 and Z_3 are purely resistive while the impedances Z_2 and Z_4 are the combinations of resistance and reactance. The currents in the branches Z_2 and Z_4 lag by 60° from the currents in the branches Z_1 and Z_3. The vertical branch B-D consists of inverse time characteristics relay. The relay has negligible impedance.

The current I_R gets divided into two equal parts I_1 and I_2. And I_2 lags I_1 by 60°. The phasor diagram is shown in the Fig. 2.18.2

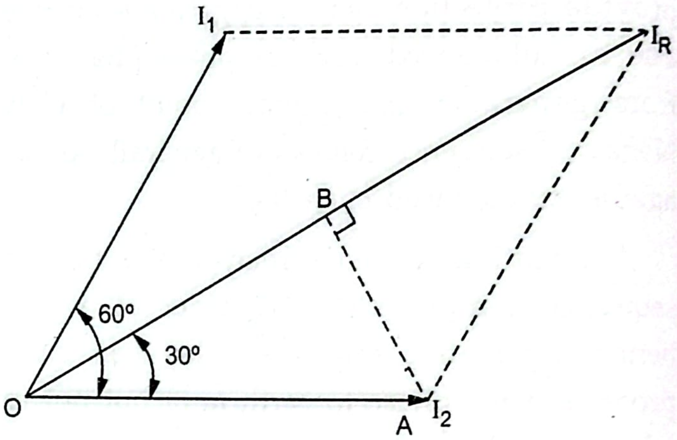


Fig. 2.18.2

$$\bar{I}_1 + \bar{I}_2 = \bar{I}_R$$

Let $$I_1 = I_2 = I$$

The perpendicular is drawn from point A on the diagonal meeting it at point B, as shown in the Fig. 2.18.2. This bisects the diagonal.

$$\therefore \quad OB = \frac{I_R}{2}$$

Now in triangle OAB,

$$\cos 30 = \frac{OB}{OA}$$

$$\therefore \quad \frac{\sqrt{3}}{2} = \frac{\left(\frac{I_R}{2}\right)}{I}$$

$$\therefore \quad I = \frac{I_R}{\sqrt{3}} = I_1 = I_2 \qquad \ldots (2.18.1)$$

Now I_1 leads I_R by 30° while I_2 lags I_R by 30°.

Similarly the current I_B gets divided into two equal parts I_3 and I_4. The current I_3 lags I_4 by 60°. From equation (2.18.1) we can write,

$$\frac{I_B}{\sqrt{3}} = I_3 = I_4 \qquad \ldots (2.18.2)$$

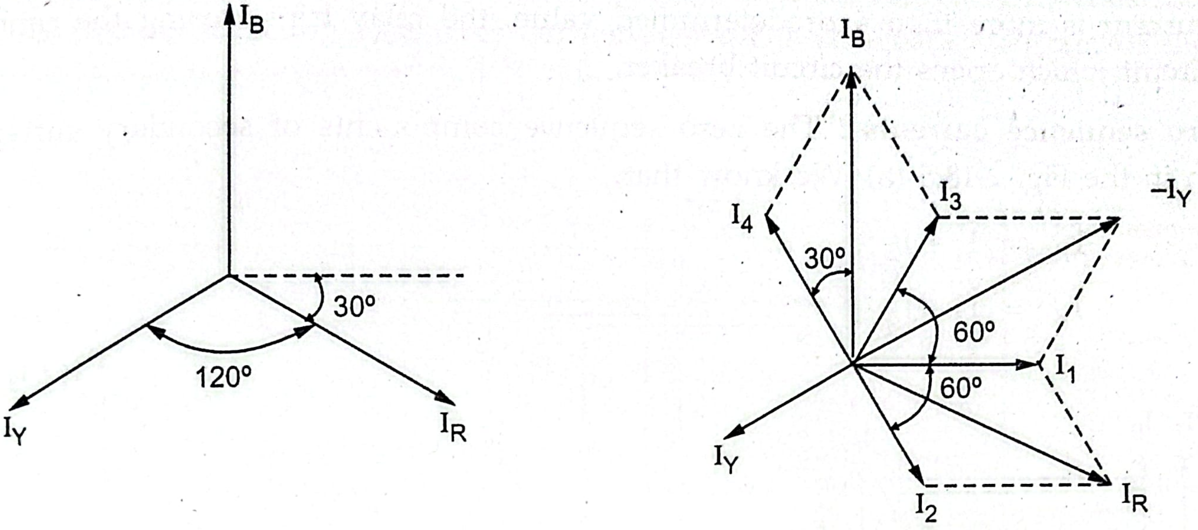
The current I_4 leads I_B by 30° while current I_3 lags I_B by 30°.

The current entering the relay at the junction point B in the Fig. 2.18.1 is the vector sum of I_1, I_3 and I_Y.

$$\therefore \quad I_{relay} = \bar{I}_1 + \bar{I}_3 + \bar{I}_Y$$

$$= I_Y + \frac{I_R}{\sqrt{3}} \text{ (leads } I_R \text{ by } 30°) + \frac{I_B}{\sqrt{3}} \text{ (lags } I_B \text{ by } 30°)$$

The vector sum is shown in the Fig. 2.18.3 when the load is balanced and no negative sequence currents exist.



(a) C. T. secondary currents (b) Vector sum

Fig. 2.18.3

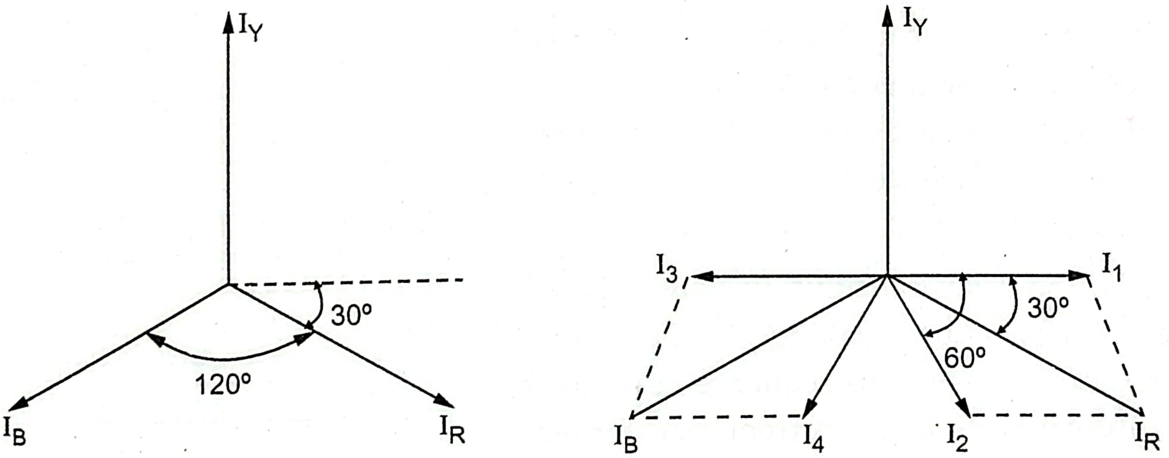
It can be seen from the Fig. 2.18.3 that,

$$\bar{I}_1 + \bar{I}_3 = -\bar{I}_Y$$

$$\therefore \quad \bar{I}_1 + \bar{I}_3 + \bar{I}_Y = 0$$

Thus the current entering the relay at point B is zero. Similarly the resultant current at junction D is also zero. Thus the relay is inoperative for a balanced system.

Now consider that there is unbalanced load on generator or motor due to which negative sequence currents exist. The phase sequence of C.T. secondary currents is as shown in the Fig. 2.18.4 (a). The vector diagram of I_1, I_3 and I_Y is shown in the Fig. 2.18.4 (b) under this condition.



(a) C.T. secondary currents (b) Vector sum

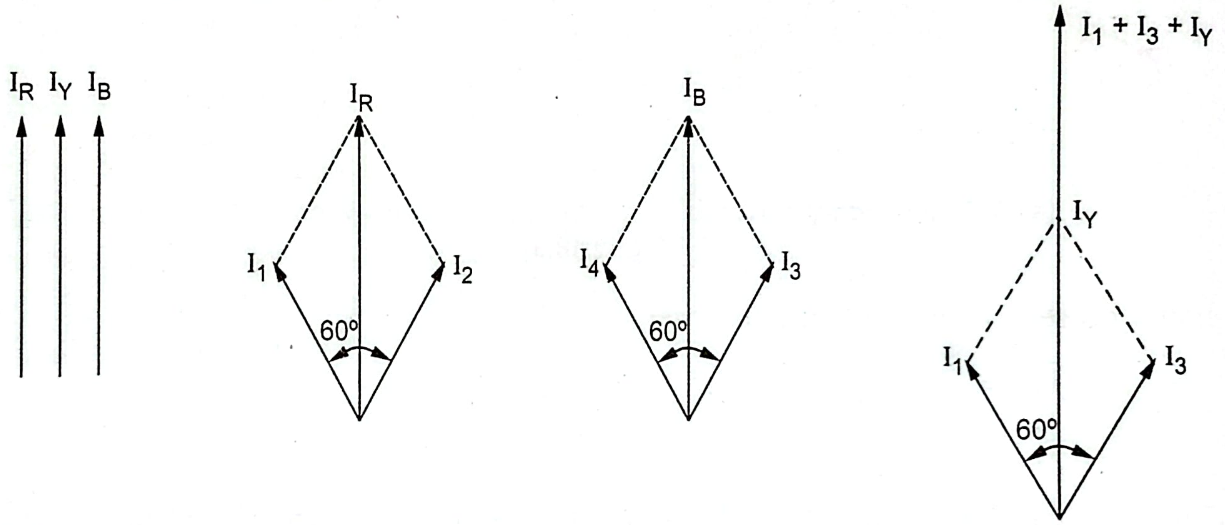
Fig. 2.18.4 Negative sequence currents

The components I_1 and I_3 are equal and opposite to each other at the junction point B. Hence I_1 and I_3 cancel each other. Now the relay coil carries the current I_Y and when this current is more than a predetermined value, the relay trips closing the contacts of trip circuit which opens the circuit breaker.

Zero sequence currents : The zero sequence components of secondary currents are shown in the Fig. 2.18.5 (a). We know that,

$$\bar{I}_R = \bar{I}_1 + \bar{I}_2$$

$$\bar{I}_B = \bar{I}_3 + \bar{I}_4$$



(a) (b) (c) (d)

Fig. 2.18.5 Zero sequence currents

These sums are shown in the Fig. 2.18.5 (b) and (c). It can be seen from the Fig. 2.18.5 (d) that,

$$\bar{I}_1 + \bar{I}_3 = \bar{I}_Y \text{ in phase with } I_Y$$

The total current through relay is $\bar{I}_1 + \bar{I}_3 + \bar{I}_Y$. Thus under zero sequence currents the total current of twice the zero sequence current flows through the relay. Hence the relay operates to open the circuit breaker.

To make the relay sensitive to only negative sequence currents by making it inoperative under the influence of zero sequence currents is possible by connecting the current transformers in delta as shown in the Fig. 2.18.6. Under delta connection of current transformers, no zero sequence current can flow in the network.

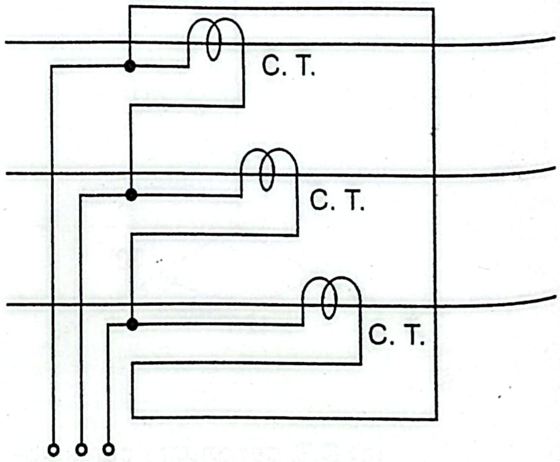


Fig. 2.18.6 Delta connection of C.T.s

2.18.1 Induction Type Negative Sequence Relay

Another commonly used negative sequence relay is induction type. Its construction is similar to that of induction type over current relay. The schematic diagram of this type of relay is shown in the Fig. 2.18.7.

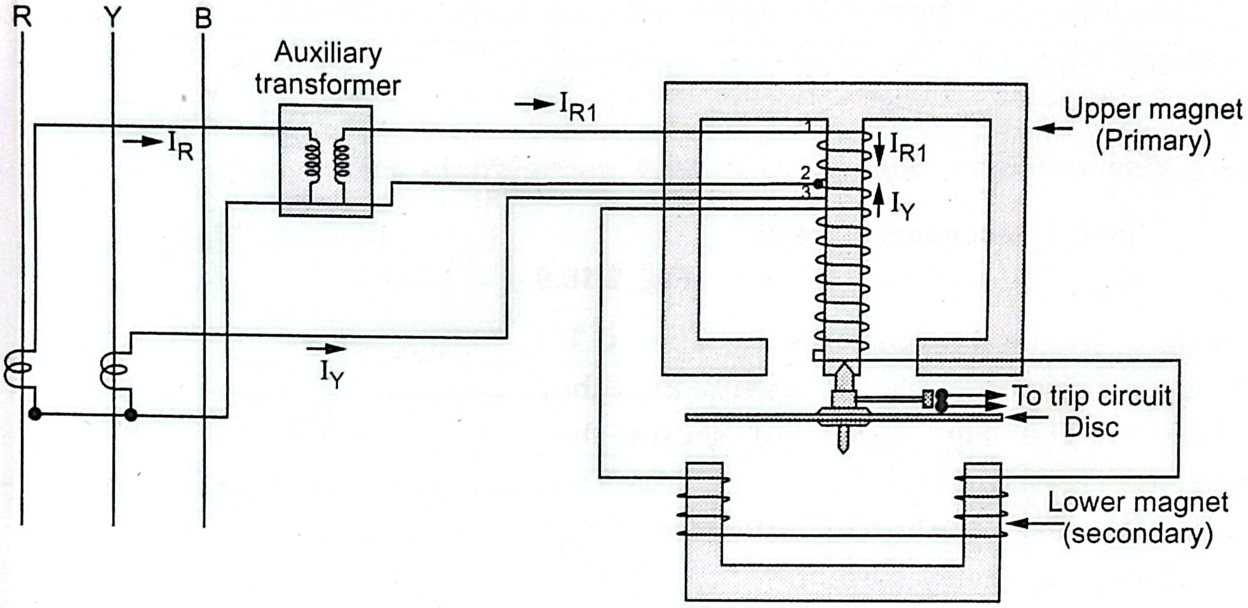


Fig. 2.18.7 Induction type negative sequence relay

The central limb of upper magnet carries the primary which has a centre tap. Due to this, the primary winding has three terminal 1, 2, and 3. The section 1 - 2 is energized from the secondary of an auxiliary transformer to R-phase. The section 2 - 3 is directly energized from the Y-phase current.

The auxiliary transformer is a special device having an air gap in its magnetic circuit. With the help of this, the phase angle between its primary and secondary can be easily adjusted. In practice it is adjusted such that output current lags by 120 ° rather than usual 180° from the input.

So, I_R = Input current of auxiliary transformer

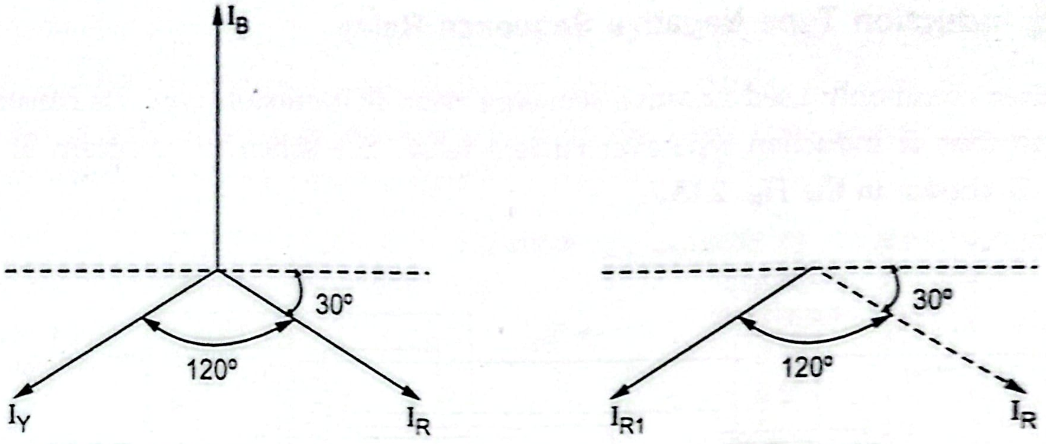
I_{R1} = Output current of auxiliary transformer

and I_{R1} lags I_R by 120 °

Hence the relay primary carries the current which is phase difference of I_{R1} and I_Y.

Positive sequence currents : The C.T. secondary currents are shown in the Fig. 2.18.8 (a). The Fig. 2.18.8 (b) shows the position of vector I_{R1} lagging I_R by 120 °. The Fig. 2.18.8 (c) shows the vector sum of I_{R1} and $-I_Y$.

The phase difference of I_{R1} and I_Y is the vector sum of I_{R1} and $-I_Y$. It can seen from the Fig. 2.18.8 (c) that the resultant is zero. Thus the relay primary current is zero and relay is inoperative for positive sequence currents.

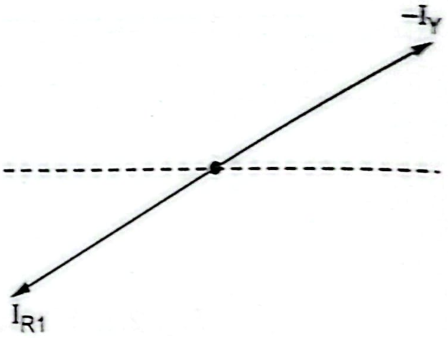


(a) C.T. secondary currents (b) Current I_{R1}

Fig. 2.18.8

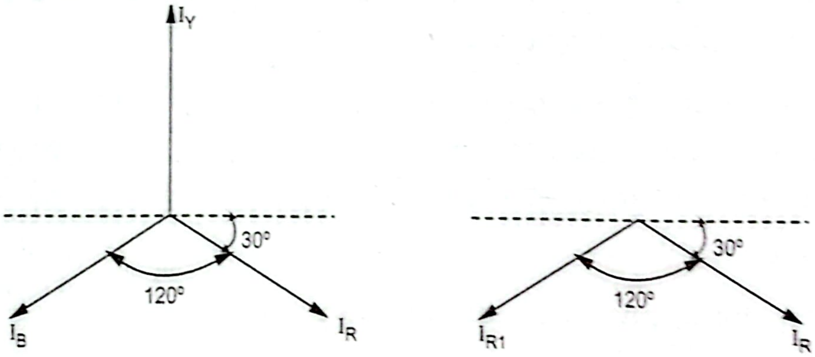
Negative sequence currents : The C.T. secondary currents are shown in the Fig. 2.18.9 (a). The Fig. 2.18.9 (b) shows the position of I_{R1} lagging I_R by 120°. The Fig. 2.18.9 (c) shows the vector difference of I_{R1} and I_Y which is the relay current.

Under negative sequence currents, the vector difference of I_{R1} and I_Y results into a current I as shown in the Fig. 2.18.9 (c). This current I flows through the primary coil of the relay.

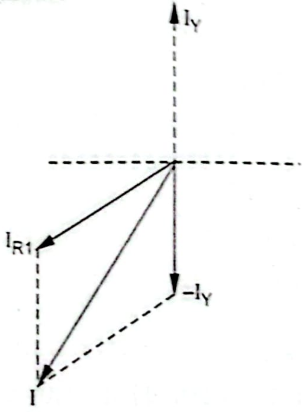


(c) Relay current

Fig. 2.18.8 Positive sequence currents



(a) C.T. secondary currents (b) Current I_{R1}



(c) Relay current

Fig. 2.18.9 Negative sequence currents

Under the influence of current I, the relay operates. The disc rotates to close the trip contacts and it opens the circuit breaker.

This relay is inoperative for zero phase sequence currents. But the relay can be made operative for the flow of zero sequence currents also by providing an additional winding on the central limb of the upper magnet of the relay. This winding is connected in the residual circuit of the three line C.T.s. This relay is called induction type negative and zero sequence relay.

The schematic arrangement of induction type negative and zero sequence relay is shown in the Fig. 2.18.10.

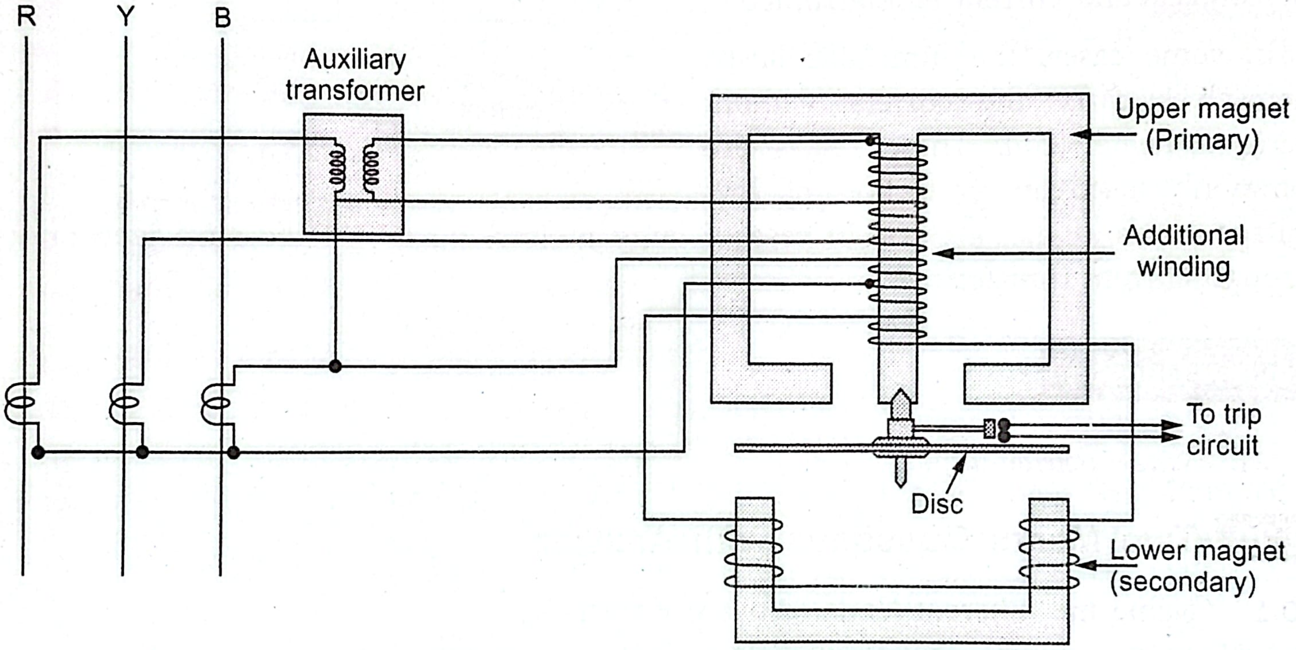


Fig. 2.18.10 Induction type negative and zero sequence relay

Review Question

1. *With neat diagram, describe the construction and principle of operation of negative sequence relay.* **AU : May-06, 14, 15, 18,19, Dec.13, Marks 8**

2.19 Thermal Relays

Thermal relays work on the principle of heating effect of an electric current in the relay coil. Instead of the measurement of temperature, these relays sense the temperature rise produced by the current.

In a simplest thermal relay, a bimetallic strip is used. The strip is mounted above a resistance coil carrying current to produce necessary heating effect. The spring is used to make the connection between contacts and the strip. The insulated lever arm is used to carry the contact which is pivoted. To have variable settings, the tension in the spring can be adjusted. The Fig. 2.19.1 shows the schematic diagram of thermal relay.

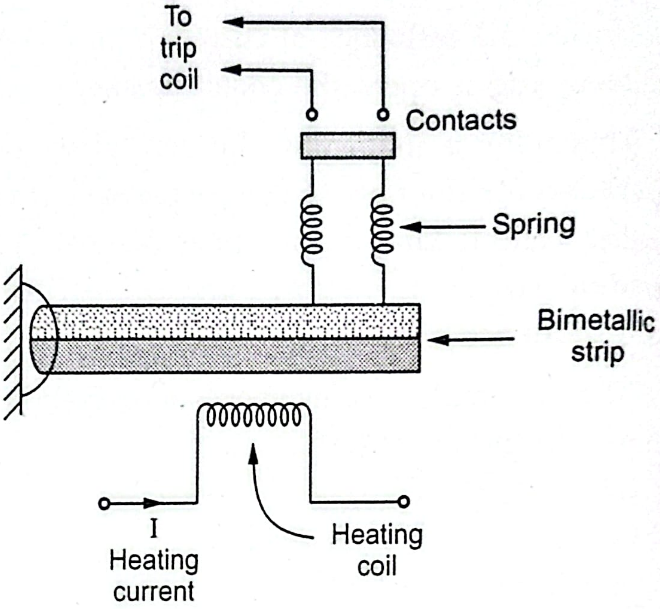


Fig. 2.19.1

Under normal conditions, the heating due to current I is not enough to heat the strips and contacts remain closed as strip remains straight.

When there is overloading, then the current I increases beyond safe value producing very high I^2R losses and corresponding large heat. Thus the strip gets heated up and bends. Due to the bending of the strip, the spring opens the contacts and current is interrupted.

In some cases, the bimetallic strips themselves carry the current without using a heater coil. These relays are commonly used in protection of low voltage a.c. and d.c. motors. In case of large motors, the bimetallic strip is connected through current transformer.

Review Question

1. *Write a note on thermal relays.*

2.20 Two Marks Questions with Answers

Q.1 Name the different kinds of overcurrent relays.

Ans. : Induction type non-directional overcurrent relay, induction type directional overcurrent relay, instantaneous overcurrent relay, inverse definite time overcurrent relay, inverse definite minimum time overcurrent relay, very inverse overcurrent relay.

Q.2 Define energizing quantity.

Ans. : The current or voltage which is used to put the relay into operation by activating it is called an energizing quantity.

Q.3 Give the applications of electromagnetic relays. **AU : Dec.-08, 10**

Ans. :

1. Protection of a.c. and d.c. equipments.
2. The over/ under voltage and over / under current protection of various equipments.
3. For the differential protection.
4. In the definite time lag overcurrent and earth fault protection.

Q.4 What are the necessary conditions for two alternating fluxes acting on a common rotor ? **AU : May-13**

Ans. : a) There must be some phase shift between the two alternating fluxes

b) The phase shift between the two alternating fluxes must be 90° for maximum torque.

Q.5 What are the advantages of overcurrent relays over electromagnetic types ?

AU : May-08

Ans. : The advantages are,

1. Very high speed of operation.
2. Fast reset.
3. Directional feature may be present.

Q.6 What are over and under current relays ? **AU : Dec.-22**

Ans. : Overcurrent relays are those which operate when the current in a line or equipment exceeds a predetermined value. Undercurrent relays are those which operate whenever the current in an equipment or line drops below a predetermined value.

Q.7 Mention any two applications of differential relay. **AU : May-11, Dec.-22**

Ans. : Protection of generator and generator transformer unit; protection of large motors and bus bars.

Q.8 What is biased differential beam relay ?

Ans. : The biased beam relay is designed to operate to the differential current in terms of its fractional relation to the actual current flowing through the protected circuit. It is essentially an over-current balanced beam relay type with an additional restraining coil. The restraining coil produces a bias force in the opposite direction to the operating force.

Q.9 What are the advantages of percentage differential relay over a simple differential relay ? **AU : Dec.-04, May-05**

Ans. :

1. Under through fault conditions the bias force produced due to restraining coil is greater than operating force produced by operating coil hence relay is inoperative. Thus false operation of relay is not possible.
2. Though the C.T.s are not perfectly matched, the inaccurate operation of relay is not possible due to restraining coil.
3. Pilot cable parameters does not affect the operation of the relay.
4. It is insensitive to the saturation of the current transformers.

Q.10 State the disadvantages of simple current differential relay.

Ans. : 1. The impedance of pilot cables causes a slight difference between the currents due to which relay may get operated inaccurately.

2. Heavy through current flows may operate the relay inaccurately.

3. Under severe through fault conditions, C.T.s may get saturated and can cause unequal secondary currents which can cause inaccurate operation of the relay.
4. Under heavy current flows, pilot wire capacitances may cause inaccurate operation of the relay.

Q.11 Mention the types of differential relays.

Ans. : 1. Current differential relay 2. Biased beam relay or percentage differential relay 3. Voltage balance differential relay.

Q.12 Draw the different overcurrent relay characteristics based on operating time.
[Refer section 2.6] **AU : May-05, Dec.-05,09**

Q.13 Name the different types of induction relays.

Ans. : 1. Shaded pole type 2. Watt hour meter type 3. Induction cup type.

Q.14 Why electromagnetic relays are useful for both a.c. and d.c. equipments ?

Ans. : The electromagnetic force produced due to the operating quantity which is exerted on plunger is proportional to the square of the flux in the air gap. Neglecting saturation effect the force is proportional to the square of the operating current. Due to the square response electromagnetic relays are useful for both a.c. and d.c. equipments.

Q.15 State any four advantages of electromagnetic relays.

Ans. :

1. Can be used for both a.c. and d.c.
2. Fast operation and fast reset.
3. Compact, simple, reliable and robust.
4. High operating speed with operating time in few milliseconds.
5. These are almost instantaneous in operation.

Q.16 State disadvantages of electromagnetic relays.

Ans. : 1. The directional feature is absent.
2. Due to the fast operation the working can be affected by the transients.

Thus false operation due to transients is possible.

Q.17 State the advantages of induction type relays.

Ans. :

1. High, low and adjustable speeds can be obtained.
2. Various shapes of time against operating quantity curves can be obtained.
3. Directional feature can be incorporated.

Q.18 What is the purpose of plug setting ?

Ans. : Plug setting is used to change the number of turns of the operating coil to get a particular pick up value.

Q.19 What are the features of directional relay ? **AU : May-11**

Ans. : 1. High speed operation 2. High sensitivity

3. Ability to operate at low voltages 4. Adequate short-time thermal ratio

Q.20 Determine plug setting multiplier of a 5 ampere, 3 second over current relay having a current setting of 125 % and a time setting multiplier of 0.6 connected to supply circuit through a 400 / 5 current transformer when the circuit carries a fault current of 4000 A. **AU : May-18**

Ans. : The PSM is given by,

$$\text{PSM} = \frac{\text{Fault current in relay coil}}{\text{Rated secondary C.T. current} \times \text{Current setting}}$$

$$\text{Fault current in relay coil} = \text{Line fault current} \times \text{C.T. ratio} = 4000 \times \frac{5}{400} = 50\text{ A}$$

$$\text{PSM} = \frac{50}{5 \times 1.25} = 8 \qquad \text{... Current setting 125 \%}$$

Q.21 What is meant by directional relay ? **AU : May-12**

Ans. : The directional relay means the relay operates for the specific direction of the actuating quantity in the circuit. A **directional relay** is one that functions when input current is in a predetermined phase position when compared to a reference, or polarizing quantity. The polarizing quantity may be a reference voltage or current.

Q.22 Why under frequency relay is required in a power system ? **AU : May-12**

OR What is an under frequency relay ? **AU : May-19**

Ans. : When the load on alternator increases then the speed decreases. The frequency is directly proportional to the speed hence the frequency decreases which is not desirable. Thus for load frequency control, the under frequency relay is required in the generator protection scheme.

Thus if frequency decreases beyond the settings, it is necessary to protect the system from underfrequency. The relay used for this purpose is called under frequency relay.

Q.23 What is meant by differential relay ? **AU : May-13, 15**

Ans. : A differential relay is defined as the relay that operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined value. Thus in a current differential relay, a relay operates on the result of comparison between the phase angle and magnitudes of the currents entering and leaving the system to be protected.

Q.24 Write the function of under frequency relay. **AU : Dec.-13, 14**

Ans. : The frequency relay is connected to the secondary of voltage transformer. The two pairs of coils are connected in parallel to the supply voltage through impedances.

The impedances are the functions of frequency. At normal frequency the impedances are tuned, balancing each other and no torque is experienced by the rotor of the relay. As frequency decreases, there is unbalance in the impedances due to which rotor of the relay experiences a torque and the relay operates.

Q.25 What is the difference between circulating current differential protection and balanced voltage differential protection ? **AU : Dec.-05**

Ans. : In circulating current differential protection, the differential current produces the operating force to operate the relay. In voltage balance relay, the voltage drop is caused due to the mismatching of currents which produces the operating force to operate the relay.

Q.26 A relay is connected to 400/5 ratio current transformer with current setting of 150 %. Calculate the PSM when the fault current is 4000 A. **AU : Dec.-11, 16**

Ans. : The PSM is given by,

$$\text{PSM} = \frac{\text{Fault current in relay coil}}{\text{Rated secondary C.T.current} \times \text{Current setting}}$$

Fault current in relay coil = Line fault current × C.T. ratio

$$= 4000 \times \frac{5}{400} = 50\text{ A}$$

$$\text{PSM} = \frac{50}{5 \times 1.5} = 6.667$$

Q.27 Name the important distance relays. **AU : May-14**

Ans. : 1. Impedance relay 2. Reactance relay 3. Mho relay.

Q.28 State the principle of operation of impedance relay.

Ans. : The impedance relay works based on the ratio of voltage V and current I of the circuit to be protected. When the fault occurs in the protected zone then the voltage drops and current increases. Hence the ratio V/I i.e. impedance reduces to very small value. When the impedance reduces than its predetermined value then the relay trips and opens the circuit breaker.

Q.29 Why impedance relay is called voltage restrained relay ?

Ans. : In an impedance relay there are two elements. One produces a torque proportional to current while other produces a torque proportional to voltage. The torque produced by the current element is used as an operating torque while the torque produced by the voltage element opposes the operating torque. Hence the torque produced by the voltage element is the restraining torque or reset torque and the relay is called voltage restrained relay.

Q.30 Show the characteristics of an impedance relay on R-X diagram.

Ans. :

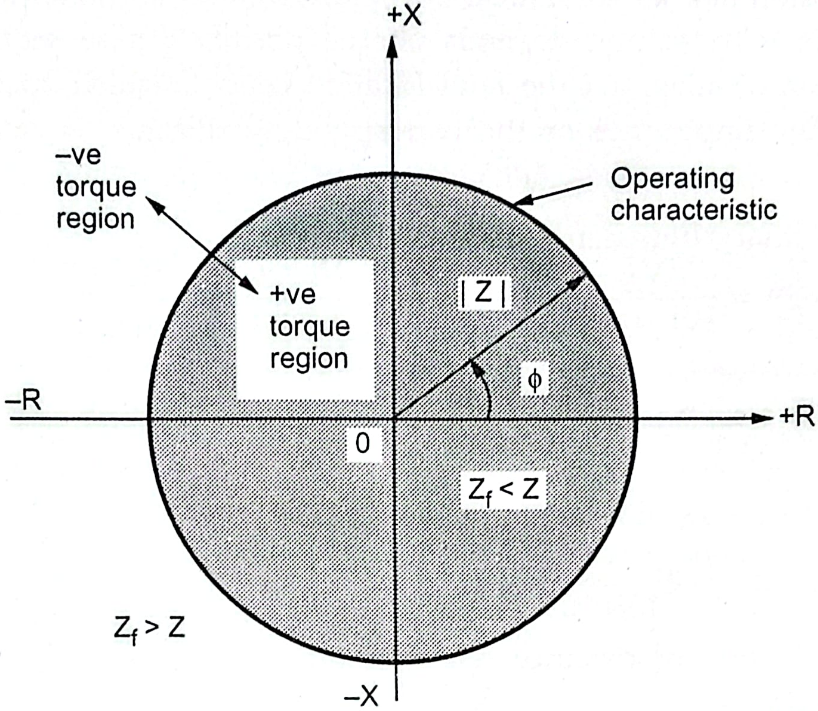


Fig. 2.20.1 Characteristic on R-X diagram

Q.31 State the disadvantages of plane impedance relay.

Ans. : 1. It is nondirectional hence can operate for the faults on both sides of a point where relay is connected.

2. When the fault occurs, arc exists. The arc resistance of line fault affects the performance of the relay.
3. As a large area is covered by the circle on each side on R-X plane, the power swings can affect the performance of the relay.

Q.32 What is reactance relay ?

Ans. : A relay which is sensitive to the reactive part of the impedance seen and trips if the reactive part is less than a particular predetermined value is called a reactance relay.

Q.33 State the use of distance relays. **AU : Dec.-06**

Ans. : Distance relays are generally used for primary and backup protection for transmission and distribution lines.

Q.34 State the merits of mho relay.

Ans. : 1. Faster operation 2. Simpler co-ordination

3. Reduced effect of fault current magnitudes 4. Inherent directional characteristics.

Q.35 What is the secondary positive sequence impedance seen by the distance relay for a 50 mile, 138 kV transmission line provided with 600/5 star connected C.T.s and 138000/115 star connected P.T.s. Assume the impedance of transmission line as 0.8 Ω/mile. **AU : Dec.-04**

Ans. : The distance relay setting depends on the positive phase sequence impedance between the position of relay and the fault location beyond which operation of a given relay unit stops. The impedance or the corresponding distance is called **reach** of the relay.

For converting primary impedance to secondary value,

$$Z_{sec} = \frac{V_2}{I_2} = \frac{V_1}{\text{P.T. ratio}} \times \frac{\text{C.T. ratio}}{I_1} = \frac{V_1}{I_1} \times \frac{\text{C.T. ratio}}{\text{P.T. ratio}}$$

$$\therefore \quad \boxed{Z_{sec} = Z_{pri} \times \frac{\text{C.T. ratio}}{\text{P.T. ratio}}}$$

For given line, $Z_{pri} = 0.8\ \Omega/\text{mile} \times 50\ \text{miles} = 40\ \Omega$

$$\therefore \quad Z_{sec} = 40 \times \frac{600}{5} \times \frac{115}{138000} = 4\ \Omega$$

Usually the first zone of distance relays is adjusted so as to reach 75 % of the length of two ended line.

∴ Secondary positive sequence impedance to reach 75 % length.

$$= 0.75 \times Z_{sec} = 0.75 \times 4 = \mathbf{3\ \Omega}$$

Q.36 In what way a distance relay is superior to over current protection for protection of transmission lines ? **AU : Dec.-15**

Ans. : The distance relays are superior to over current relays for protection of transmission lines as the distance relays are not much affected by the changes in the short circuit current magnitude as compared to overcurrent relays and also less affected by the changes in the generating capacity and system configuration.

Q.37 Where is negative phase sequence relay employed ? **AU : Dec.-15**

Ans. : The negative phase sequence relays are used to provide protection against negative sequence component of unbalanced currents existing due to unbalanced loads or phase to phase faults. These relays are generally employed to give protection to generators and motors against unbalanced currents.

Q.38 Why a shading ring is provide in a induction disc relay ? **AU : May-17**

Ans. : For the working of induction relay, it is necessary to have two flux components out of phase with each other. The total air gap flux produced by the coil current is split into two out of phase flux components due to the shading ring.

Q.39 Write the torque equation of the universal relay. **AU : Dec.-17**

Ans. : The universal relay torque equation is,

$$T = K_3 VI \cos(\theta - \tau) - K_4$$

where θ = angle between V and I

τ = Maximum torque angle

K_4 = Torque produced by control spring

Q.40 Give the principle of negative sequence relay. **AU : Dec.-17**

Ans. : When there is unbalanced load, the current can be divided into three components, positive, negative and zero. The negative sequence components rotates at synchronous speed in a direction opposite to the direction of rotor. The negative sequence filter is used in the relay to seperate the negative sequence component and allow it to pass through the relay coil. If this component is more than the setting of the relay then the relay operates.

Q.41 Mention the principle of operation of distance relay. **AU : May - 18**

Ans. : The distance relays work on the principle of measurement of voltage to current ratio. Such a ratio is nothing but an impedance which is an electrical measure of the distance along a line upto a fault point. The relay operates when the ratio V to I i.e. impedance is less than a predetermined setting value.

Q.42 How protective relays are classified based on their functions ? **AU : Dec. - 18**

Ans. : The relays are classified as,

i) Electromagnetic attraction type : Further classified as solenoid type, attracted armature type and balanced beam type.

ii) Induction type : Further classified as induction disc type and induction cup type.

iii) Distance type : Further classified as impedance type, reactance type and mho type.

iv) Differential type : Further classified as current differential type, voltage differential type.

v) Other types such as thermal type, rectifier type, static type, gas operated type etc.

Q.43 Differentiate time graded system and current graded system used in overcurrent protection. **AU : Dec. - 18**

Ans. : In the time graded system, time discrimination is used i.e. the time setting of relays is so graded that in the event of the fault, the smallest possible part of the system is isolated.

The discrimination is dependent only on time grading, the individual overcurrent relays can be set to any desired levels of current above the rated currents of their circuits.

In the current graded system, the relays are set to operate at progressively higher values of current as one moves towards the source. The discrimination of faulty zone is not ideal.

Q.44 Draw the R-X diagram for the reactance and mho relay. **AU : May - 19**

Ans. : Refer Fig. 2.12.3 and Fig. 2.13.2.

Q.45 Write the torque equation of induction relay. **AU : May - 22**

Ans. : The torque equation of an induction relay is,

$$F \ \alpha \ \phi_1 \phi_2 \sin\alpha$$

where ϕ_1 and ϕ_2 are the fluxes produced by the two electromagnets when alternating currents are supplied to them. These fluxes are given by,

$$\phi_1 = \phi_{1m} \sin\omega t \text{ and } \phi_2 = \phi_{2m} \sin(\omega t + \alpha)$$

2.21 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *With a neat diagram explain the working principle of a directional over current relay. Derive the torque equation and also explain about directional relay connection.* **[Section 2.9]** **[10]**

Q.2 *From the universal torque equation determine the condition of operation for impedance relay, reactance relay and admittance relay.* **[Sections 2.11, 2.12 and 2.13]** **[16]**

May-17

Q.3 *Explain the construction and operating principle of impedance type distance relay with R.X Diagram.* **[Section 2.11]** **[16]**

Q.4 *With the ncessary sketches discuss in detail about electromagnetic attraction type relay.* **[Section 2.3]** **[16]**

Dec.-17

Q.5 *With neat diagram explain the various types of electromagnetic relays.* **[Section 2.3]** **[16]**

Q.6 *Describe the construction and principle of operation of non-directional Induction type over current relay.* **[Section 2.7]** **[16]**

May-18

Q.7 *With neat sketch explain negative sequence relay.* **[Section 2.18]** **[8]**

Q.8 *Explain clearly about current balance differential relays.* **[Section 2.16.1]** **[8]**

Q.9 *Explain impedance relay with suitable R-X diagrams.* **[Section 2.11]** **[16]**

Dec.-18

Q.10 *Explain various time-current characteristics of an overcurrent relay with relevant applications. Also comment about the technique to realize those time-current characteristics using electromagnetic relays.* **[Sections 2.6, 2.7 and 2.8]** **[13]**

Q.11 *Discuss with relevant connection diagram and phasor diagram, the directional over current relay.* **[Section 2.9]** **[13]**

May-19

Q.12 *Describe the construction and principle of operation of an induction type directional over current relay.* **[Section 2.9]** **[13]**

Q.13 *With neat diagram, describe the construction and principle of operation of negative sequence relay.* **[Section 2.18]** **[13]**

(Regulation 2017)

May-22

Q.14 *Describe the construction and principle of operation of an induction type directional over current relay.* **[Section 2.9]** **[13]**

Q.15 *Explain with sketches and their R-X diagrams of impedance, mho and reactance relay.* **[Sections 2.11, 2.12 and 2.13]** **[13]**

Dec.-22

Q.16 *Discuss in detail about various types of electromagnetic relays.* **[Section 2.3)** **[13]**

Q.17 *With neat diagram, explain the construction and operation of non directional over current relay.* **[Section 2.7]** **[13]**

❑❑❑

UNIT III

3

Transformer Protection

Syllabus

Current transformers and potential transformers and their applications in protection schemes - Protection of transformer.

Contents

3.1 Instrument Transformers . . . . **May-04,12,17,** · · · · · · · · · · · *Marks 6*
3.2 Introduction to Transformer Protection
3.3 Possible Transformer Faults . . . . **Dec.-06,17,** · · · · · · · · · · · · · *Marks 6*
3.4 Percentage Differential Protection for Transformers . . . . **May-04,05,11,14,17,19, April-05, Dec.-05,07,08,10,12,13,17,22,** · *Marks 16*
3.5 Problems Encountered in Differential Protection . . . . **May-04,07, 19 Dec.-08,11,15,18,** · · · · · · · *Marks 13*
3.6 Frame Leakage Protection. . . . . **May-19** · · · · · · · · · · · · · · · · · · *Marks 4*
3.7 Buchholz Relay (Incipient Fault Protection) . . . **Dec.-04,14,16, May-06,13,18,19** · · · · · · · · · *Marks 8*
3.8 Two Marks Questions with Answers
3.9 University Questions with Answers (Long Answered Questions)

3.1 Instrument Transformers

AU : May-04,12,17

In heavy currents and high voltage a.c. circuits, the measurement can not be done by using the method of extension of ranges of low range meters by providing suitable shunts. In such conditions, specially constructed accurate ratio transformers called **instrument transformers**. These can be used, irrespective of the voltage and current ratings of the a.c. circuits. These transformers not only extend the range of the low range instruments but also isolate them from high current and high voltage a.c. circuits. This makes their handling very safe. These are generally classified as (i) current transformers and (ii) potential transformers.

3.1.1 Current Transformers (C.T.)

The large alternating currents which can not be sensed or passed through normal ammeters and current coils of wattmeters, energymeters can easily be measured by use of current transformers along with normal low range instruments.

A transformer is a device which consists of two windings called primary and secondary. It transfers energy from one side to another with suitable change in the level of current or voltage. A current transformer basically has a primary coil of one or more turns of heavy cross-sectional area. In some, the bar carrying high current may act as a primary. This is connected in series with the line carrying high current.

The secondary of the transformer is made up of a large number of turns of fine wire having small cross-sectional area. This is usually rated for 5 A. This is connected to the coil of normal range ammeter. Symbolic representation of a current transformer is as shown in the Fig. 3.1.1.

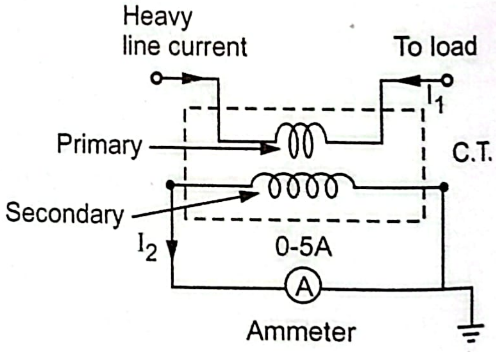


Fig. 3.1.1 Current transformer

3.1.1.1 Working Principle

These transformers are basically step up transformers i.e. stepping up a voltage from primary to secondary. Thus the current reduces from primary to secondary. So from current point of view, these are step down transformers, stepping down the current value considerably from primary to secondary.

Let N_1 = Number of turns of primary, N_2 = Number of turns of secondary

I_1 = Primary current, I_2 = Secondary current

For a transformer, $\boxed{\frac{I_1}{I_2} = \frac{N_2}{N_1}}$

As N_2 is very high compared to N_1, the ratio I_1 to I_2 is also very high for current transformers. Such a current ratio is indicated for representing the range of current transformer. For example, consider a 500 : 5 range then it indicates that C.T. Steps down the current from primary to secondary by a ratio 500 to 5.

$$\therefore \qquad \frac{I_1}{I_2} = \frac{500}{5}$$

Knowing this current ratio and the meter reading on the secondary, the actual high line current flowing through the primary can be obtained.

Example 3.1.1 *A 250 : 5, current transformer is used along with an ammeter. If ammeter reading is 2.7 A, estimate the line current.*

Solution :

$$\frac{I_1}{I_2} = \frac{250}{5}$$

But as ammeter is in secondary, $I_2 = 2.7$ A i.e. $\frac{I_1}{2.7} = \frac{250}{5}$

$$\therefore \qquad I_1 = 135 \text{ A} \quad \text{thus line current is 135 A.}$$

3.1.2 Why Secondary of C.T. Should not be Open ?

It is very important that the secondary of C.T. should not be kept open. Either it should be shorted or must be connected in series with a low resistance coil such as current coils of wattmeter, coil of ammeter etc. If it is left open, then current through secondary becomes zero hence the ampere turns produced by secondary which generally oppose primary ampere turns becomes zero. As there is no counter m.m.f., unopposed primary m.m.f. (ampere turns) produce high flux in the core. This produces excessive core losses, heating the core beyond limits. Similarly heavy e.m.fs will be induced on the primary and secondary side. This may damage the insulation of the winding. This is danger from the operator point of view as well. It is usual to ground the C.T. on the secondary side to avoid a danger of shock to the operator.

Hence never open the secondary winding circuit of a current transformer while its primary winding is energised.

Thus most of the current transformers have a short circuit link or a switch at secondary terminals. When the primary is to be energised, the short circuit link must be closed so that there is no danger of open circuit secondary.

3.1.3 Potential Transformers (P.T.)

The basic principle of these transformers is same as current transformers. The high alternating voltage is reduced in a fixed proportion for the measurement purpose with the help of potential transformers. The construction of these transformers is similar to the normal transformer. These are extremely accurate ratio step down transformers. The windings are low power rating windings. Primary winding consists of large number of turns while secondary has less number of turns and usually rated for 110 V, irrespective of the primary voltage rating. The primary is connected across the high voltage line while secondary is connected to the low range voltmeter coil. One end of the secondary is always grounded for safety purpose. The connections are shown in the Fig. 3.1.2.

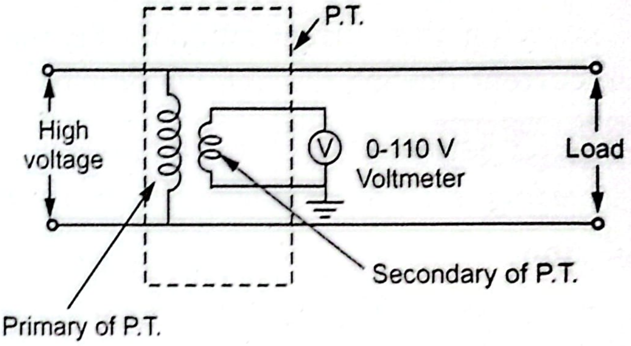


Fig. 3.1.2 Potential transformer

As a normal transformer, its ratio can be specified as,

$$\boxed{\frac{V_1}{V_2} = \frac{N_1}{N_2}}$$

So if voltage ratio of P.T. is known and the voltmeter reading is known then the high voltage to be measured, can be determined.

Example 3.1.2 *A 11000 : 110, potential transformer is used along with a voltmeter reading 87.5 V. Estimate the value of line voltage.*

Solution : For a P.T.

$$\frac{V_1}{V_2} = \frac{11000}{110} \quad \text{and} \quad V_2 = 87.5 \text{ V}$$

$$\therefore \quad \frac{V_1}{87.5} = \frac{11000}{110} \quad \text{i.e.} \quad V_1 = 8750 \text{ V}$$

This is the value of high voltage to be measured.

3.1.4 Comparison of C.T. and P.T.

The comparison of C.T. and P.T. is given in the following table,

Sr. No.	Current transformer	Potential transformer
1.	It can be treated as series transformer under virtual short circuit conditions.	It can be treated as parallel transformer under open circuit secondary.

2.	Secondary must be always shorted.	Secondary is nearly under open circuit conditions.
3.	A small voltage exists across its terminals as connected in series.	Full line voltage appears across its terminals.
4.	The winding carries full line current.	The winding is impressed with full line voltage.
5.	The primary current and excitation varies over a wide range.	The line voltage is almost constant hence exciting current and flux density varies over a limited range.
6.	The primary current is independent of the secondary circuit conditions.	The primary current depends on the secondary circuit conditions.
7.	Needs only one bushing as the two ends of primary winding are brought out through the same insulator. Hence there is saving in cost.	Two bushings are required when neither side of the line is at ground potential.

Table 3.1.1

3.1.5 Advantages and Disadvantages of Instrument Transformers

The **advantages** of instrument transformers can be listed as,

1. The normal range voltmeter and ammeter can be used along with these transformers to measure high voltage and currents.
2. The rating of low range meter can be fixed irrespective of the value of high voltage or current to be measured.
3. These transformers isolate the measurement from high voltage and current circuits. This ensures safety of the operator and makes the handling of the equipments very easy and safe.
4. These can be used for operating many types of protecting devices such as relays or pilot lights.
5. Several instruments can be fed economically by single transformer.

Disadvantage :

The only disadvantage of these instrument transformers is that they can be used only for a.c. circuits and not for d.c. circuits.

3.1.6 Applications of C.T.s and P.T.s

The C.T.s and P.T.s are used for,

1. Circulating current differential protection.
2. Over current phase fault protection.
3. Distance protection.
4. Intermediate CTs for feeding protective devices, measuring systems, relays etc.

Review Questions

1. *What are instrument transformers ? Discuss the working of current transformer and potential transformer.* **AU : May-17, Marks 16**
2. *Why secondary of C.T. should not be open ?* **AU : May-04, Marks 6**
3. *Differentiate C.T. and P.T.* **AU : May-12, Marks 6**
4. *State the advantages, disadvantages and applications of instrument transformers.*

3.2 Introduction to Transformer Protection

The transformers are static devices without having any rotating part and are totally enclosed. Hence the chances of faults occurring on transformers are much rare as compared to the faults occurring on generators. Similarly possibilities of running on abnormal conditions are also less in transformers compared to the generators.

But though the fault possibility is rare, if fault occurs, the transformer must be quickly disconnected from the system. The rare faults if not cleared quickly can get developed into the major faults which may be very serious for the transformer. Hence the protection must be provided to the transformers against possible faults.

The use of series fuses is very common in case of small distribution transformers instead of circuit breakers. Hence it is not necessary to install any automatic protective relaying equipments with the distribution transformers. But the power transformers having large ratings always need some type of automatic protective relaying equipments, to give protection against the possible faults.

3.3 Possible Transformer Faults

AU : Dec.-06, 17

The generators are subjected to the number of faults and abnormal conditions but the transformers are not. The various possible transformer faults are,

1. Overheating
2. Winding faults
3. Open circuits
4. Through faults
5. Over fluxing

Let us discuss these faults.

3.3.1 Overheating

The overheating of the transformer is basically of sustained overloads and short circuits. The permissible overload and the corresponding duration is dependent on the type of transformer and class of insulation used for the transformer. Higher loads are permissible for very short duration of time. The overloading which continues for longer time is dangerous as it causes overheating of the transformer. Similarly the failure of the cooling system, though rare, is another possible cause of overheating. Generally the thermal overload relays and temperature relays, sounding the alarm are used to provide protection against overheating. Similarly temperature indicators are also provided. On the transformers, when temperature exceeds the permissible limits, the alarm sounds and the fans are started. The thermocouples or resistance temperature indicators are also provided near the winding. These are connected in a bridge circuit. When temperature exceeds the limiting safe value, the bridge balance gets disturbed and alarm is sounded. If the corrective action is not taken within certain period of time then the circuit breaker trips.

3.3.2 Winding Faults

The winding faults are called internal faults. These faults are,

i) Phase to phase faults ii) Earth faults iii) Interturn faults.

The overheating or mechanical shocks cause to deteriorate the winding insulation. If the winding insulation is weak, there is a possibility of short circuit between the phases or between the phase and ground. Also the possibility of short circuit between the adjacent turns of the same phase winding is also possible.

When such an internal fault occurs, the transformer must be quickly disconnected from the system. If such a fault persists for longer time, there is possibility of oil fire. The differential protection is very commonly used to provide protection against such faults. But this protection is not economical for the transformers below 5 MVA for which an over current protection is used. For the high capacity transformers in addition to main differential protection, the overcurrent protection is also provided as a backup protection. For earth fault protection, the restricted earth fault protection system, neutral current relays or leakage to frame protection system is used.

3.3.3 Open Circuits

The open circuit in one of the three phases is dangerous as it causes the undesirable heating of the transformer. A separate relay protection is not provided for the open circuits as open circuits are much harmless compared to other faults. In case of such faults, the transformer can be manually disconnected from the system.

3.3.4 Through Faults

Through faults are the external faults which occur outside the protected zone. Through faults are not detected by the differential protection. If the through faults persists for long period of time, the transformer may get subjected to the thermal and mechanical stresses which can damage the transformer. The overcurrent relays with undervoltage blocking, zero sequence protection and negative sequence protection are used to give protection against through faults. The setting of the overcurrent protection not only protects the transformer but also covers the station busbar and portion of a transmission line. Such a protection acts as a backup protection for the differential protection.

3.3.5 Overfluxing

The flux density in the transformer core is proportional to the ratio of the voltage to frequency i.e. V/f. The power transformers are designed to work with certain value of flux density in the core. In the generator transformer unit, if full excitation is applied before generator reaches its synchronous speed then due to high V/f the overfluxing of core may result. Higher core flux means more core loss and overheating of the core. The saturation of magnetic circuit is also the probable cause for the overfluxing operation. The V/f relay called volts/hertz relay is provided to give the protection against overfluxing operation. This relay does not allow exciting current to flow till the generator reaches to a synchronous speed and runs to produce voltage of proper frequency. The overfluxing relays with enough time lag also can be provided.

Apart from these faults, some other faults like tap-changer faults, high voltage surges due to lightning and switching, incipient faults i.e. slow developing faults may also occur in the transformers. The Buchholz relay is used for oil immersed transformers to give the protection against incipient faults.

Review Question

1. *Describe the possible faults in transformer.* **AU : Dec.-06, 17, Marks 6**

3.4 Percentage Differential Protection for Transformers

AU : May-04,05,11,14,17,19, April-05, Dec.-05,07,08,10,12,13,17,22

The percentage differential protection or Merz-Price protection based on the circulating current principle can also be used for the transformers. This system gives protection against phase to phase faults and phase to ground faults to the power transformers.

The principle of such a protection scheme is the comparison of the currents entering and leaving the ends of a transformer. The vector difference of currents $I_1 - I_2$ passes through the operating coil while the average current $(I_1 + I_2)/2$ passes through the restraining coil. In normal conditions, the two currents at the two ends of the transformer are equal and balance is maintained. So no current flows through the operating coil of the relay and relay is inoperative. But when there is phase to phase fault or phase to ground fault, this balance gets disturbed. The difference current flows through the operating coil due to which relay operates, tripping the circuit breaker.

Compared to the differential protection used in generators, there are certain **important points** which must be taken care of while using such protection for the power transformers. These points are,

1. In a power transformer, the voltage rating of the two windings is different. The high voltage winding is low current winding while low voltage winding is high current winding. Thus there always exists difference in current on the primary and secondary sides of the power transformer. Hence if C.T.s of same ratio are used on two sides, then relay may get operated through there is no fault existing.

   To compensate for this difficulty, the current ratios of C.T.s on each side are different. These ratios depend on the line currents of the power transformer and the connection of C.T.s. Due to the different turns ratio, the currents fed into the pilot wires from each end are same under normal conditions so that the relay remains inoperative. For example if K is the turns ratio of a power transformer then the ratio of C.T.s on low voltage side is made K times greater than that of C.T.s on high voltage side.

2. In case of power transformers, there is an inherent phase difference between the voltages induced in high voltage winding and low voltage winding. Due to this, there exists a phase difference between the line currents on primary and secondary sides of a power transformer. This introduces the phase difference between the C.T. secondary currents, on the two sides of a power transformer. Though the turns ratio of C.T.s are selected to compensate for turns ratio of transformer, a differential current may result due to the phase difference between the currents on two sides. Such a differential current may operate the relay though there is no fault. Hence it is necessary to correct the phase difference.

   To compensate for this, the C.T. connections should be such that the resultant currents fed into the pilot wires from either sides are displaced in phase by an angle equal to the phase shift between the primary and secondary currents. To achieve this, secondaries of C.T.s on star connected side of a power transformer are connected in delta while the secondaries of C.T.s on delta connected side of a power transformer are connected in star.

   The Table 3.4.1 gives the way of connecting C.T. secondaries for the various types of power transformer connections.

Power transformer connections		**C. T. connections**	
Primary	Secondary	Primary	Secondary
Star	Delta	Delta	Star
Delta	Delta	Star	Star
Star	Star	Delta	Delta
Delta	Star	Star	Delta

Table 3.4.1

With such an arrangement, the phase displacement between the currents gets compensated with the oppositely connected C.T. secondaries. Hence currents fed to the pilot wires from both the sides are in phase under normal running conditions and the relay is ensured to be inoperative.

3. The neutrals of C.T. star and power transformer stars are grounded.
4. Many transformers have tap changing arrangement due to which there is a possibility of flow of differential current. For this, the turns ratio of C.T.s on both sides of the power transformer are provided with tap for of C.T.s on both sides of the power transformer are provided with tap for their adjustment.

For the sake of understanding, the connection of C.T. secondaries in delta for star side of power transformer and the connection of C.T. secondaries in star for delta side of power transformer is shown in the Fig. 3.4.1 (a) and (b).

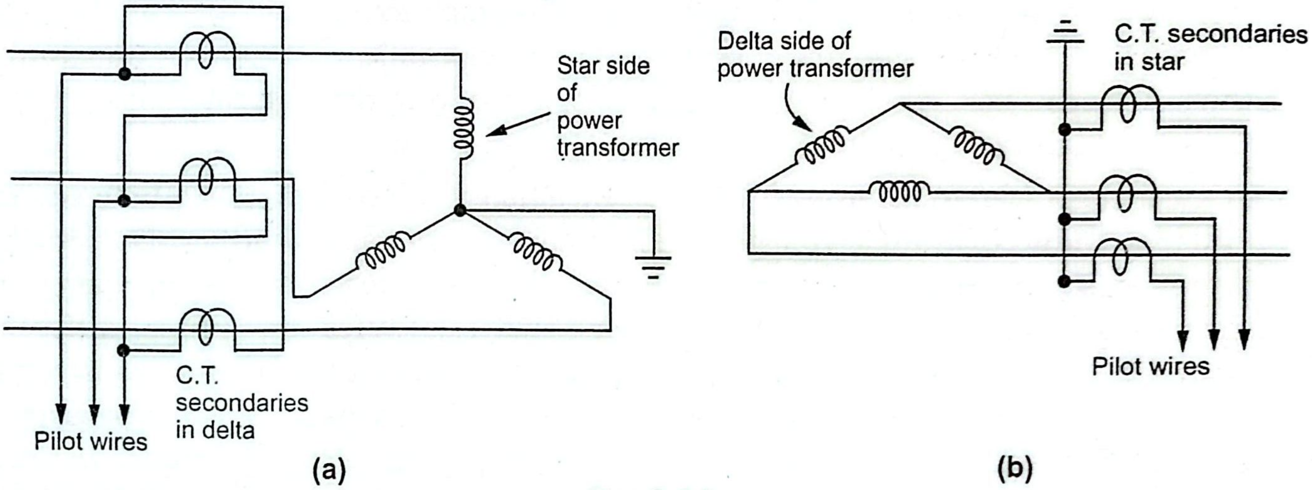

Star side of power transformer
C.T. secondaries in delta
Pilot wires
(a)
Delta side of power transformer
C.T. secondaries in star
Pilot wires
(b)

Fig. 3.4.1

3.4.1 Merz-Price Protection for Star-Delta Transformer

Let us study the Merz-Price protection for the star-delta power transformer. The primary of the power transformer is star connected while the secondary is delta connected. Hence to compensate for the phase difference, the C.T. secondaries on primary side must be connected in delta while the C.T. secondaries on delta side must be connected in star. The star point of the power transformer primary as well as the star connected C.T. secondaries must be grounded.

The circuit diagram of the scheme is shown in the Fig. 3.4.2.

The restraining coils are connected across the C.T. secondary windings while the operating coils are connected between the tapping points on the restraining coils and the star point of C.T. secondaries.

With the proper selection of turns ratio of C.T.s the coils are under balanced condition during normal operating conditions. The C.T. secondaries carry equal currents which are in phase under normal conditions. So no current flows through the relay and the relay is inoperative.

With an internal fault in power transformer windings, the balance in the C.T.s get disturbed. The operating coils of differential relay carry currents proportional to the difference of current between the two sides of a power transformer. This causes the relay operation which trips the main circuit breakers on both the sides of the power transformer.

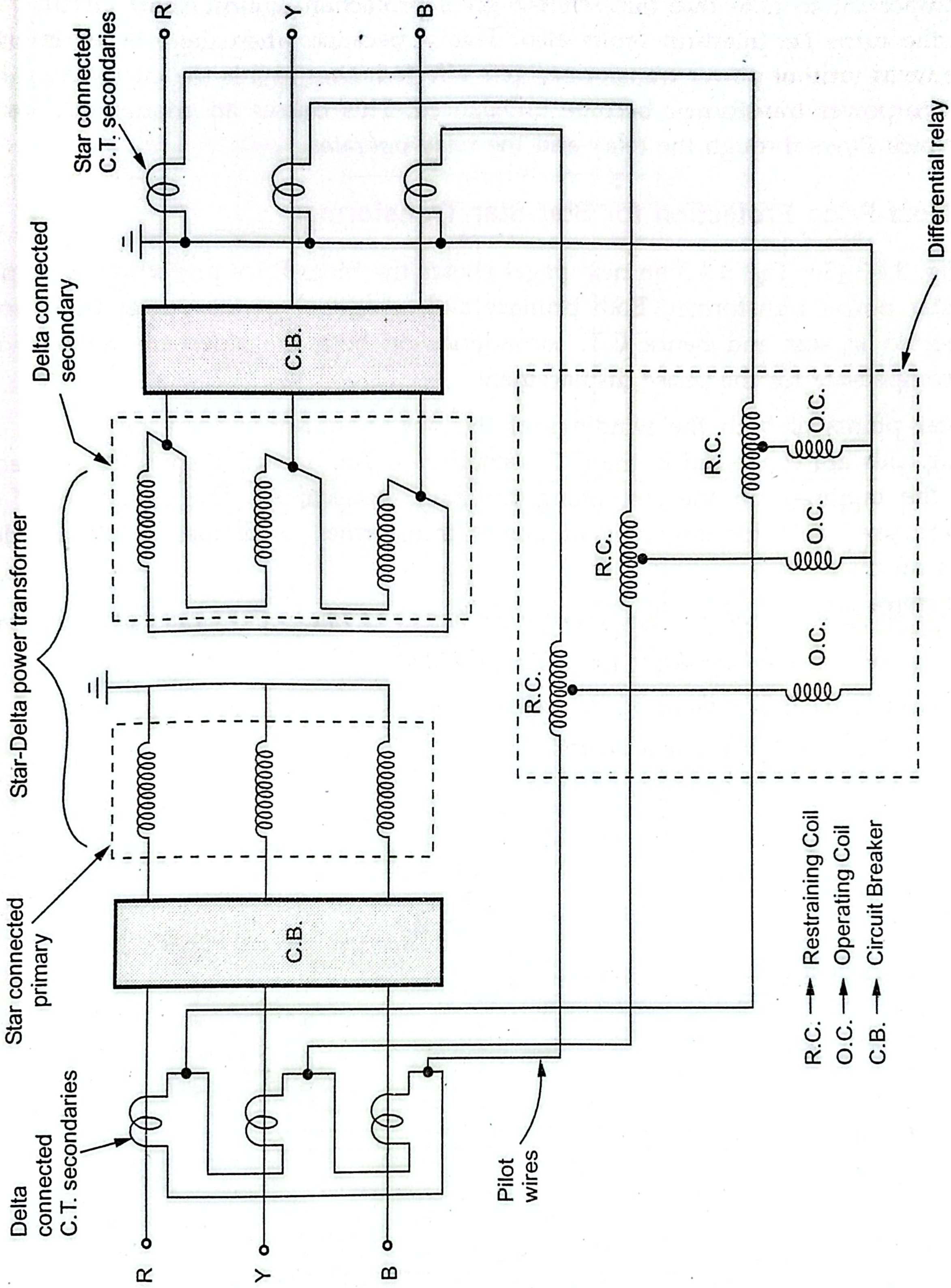

Star connected C.T. secondaries
R
Y
B
Delta connected secondary
C.B.
Star-Delta power transformer
Star connected primary
C.B.
Delta connected C.T. secondaries
R
Y
B
Pilot wires
Differential relay
R.C.
R.C.
R.C.
O.C.
O.C.
O.C.
R.C. → Restraining Coil
O.C. → Operating Coil
C.B. → Circuit Breaker

Fig. 3.4.2 Merz-Price protection for star-delta power transformer

The basic requirements of the differential relay are,

1. The differential relay must not operate on load or external faults.
2. It must operate on severe internal faults.

The relay satisfying these requirements is used in Merz-Price protection.

It is important to note that this scheme gives protection against short circuit faults between the turns i.e. interturn faults also. This is because when there is an interturn fault, the turns ratio of power transformer gets affected. Due to this the currents on both sides of the power transformer become unbalanced. This causes an enough differential current which flows through the relay and the relay operates.

3.4.2 Merz-Price Protection for Star-Star Transformer

The Fig. 3.4.3 (See Fig. 3.4.3 on next page) shows the Merz-Price protection system for the star-star power transformer. Both primary and secondary of the power transformer are connected in star and hence C.T. secondaries on both the sides are connected in delta to compensate for the phase displacement.

The star points of both the windings of the power transformer are grounded. The restraining coils are connected in the C.T. secondaries. The operating coils are connected between the tappings on the restraining coil and the ground. The operation of the scheme remains same for any type of power transformer as discussed for star-delta power transformer.

Example 3.4.1 *A three phase power transformer having a line voltage ratio of 400 V to 33 kV is connected in star-delta. The C.T.s on 400 V side have current ratio as 1000 / 5. What must be the C.T. ratio on 33 kV side ?*

Assume current on 400 V side of transformer to be 1000 A.

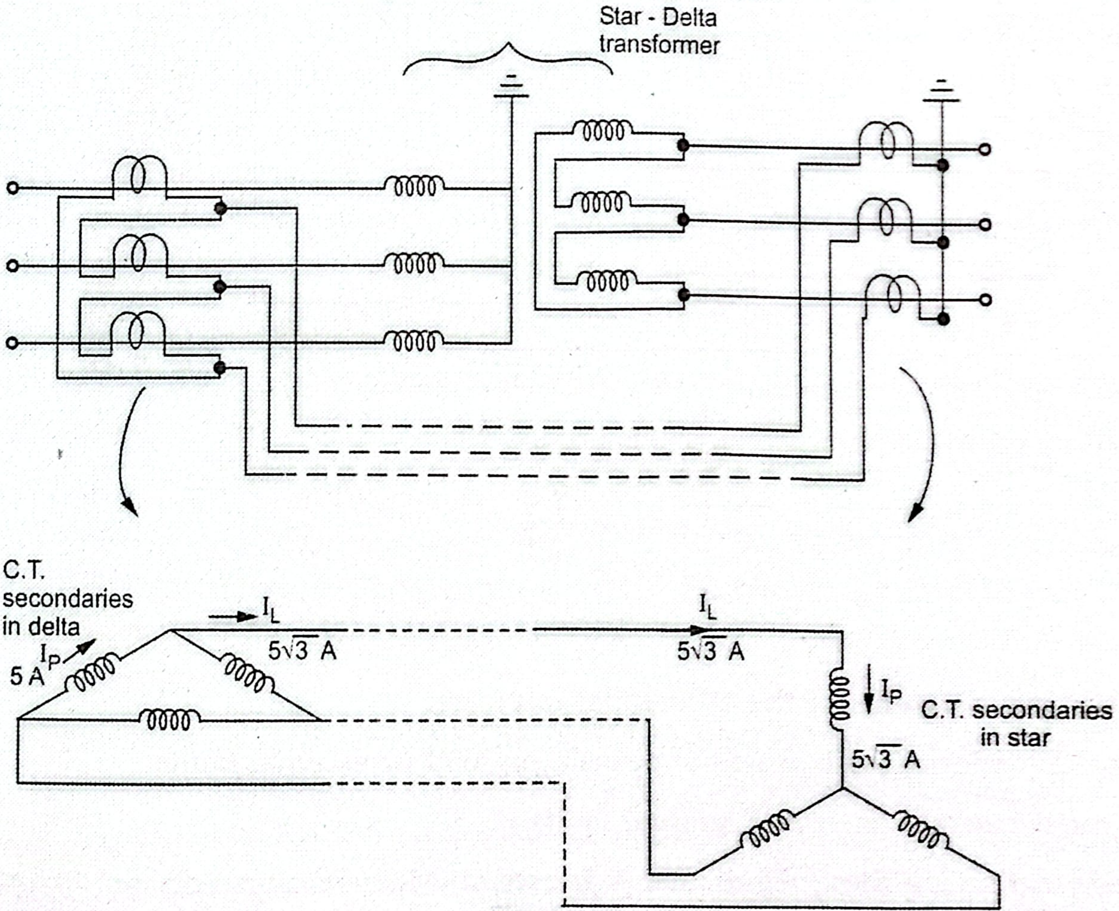


Fig. 3.4.4

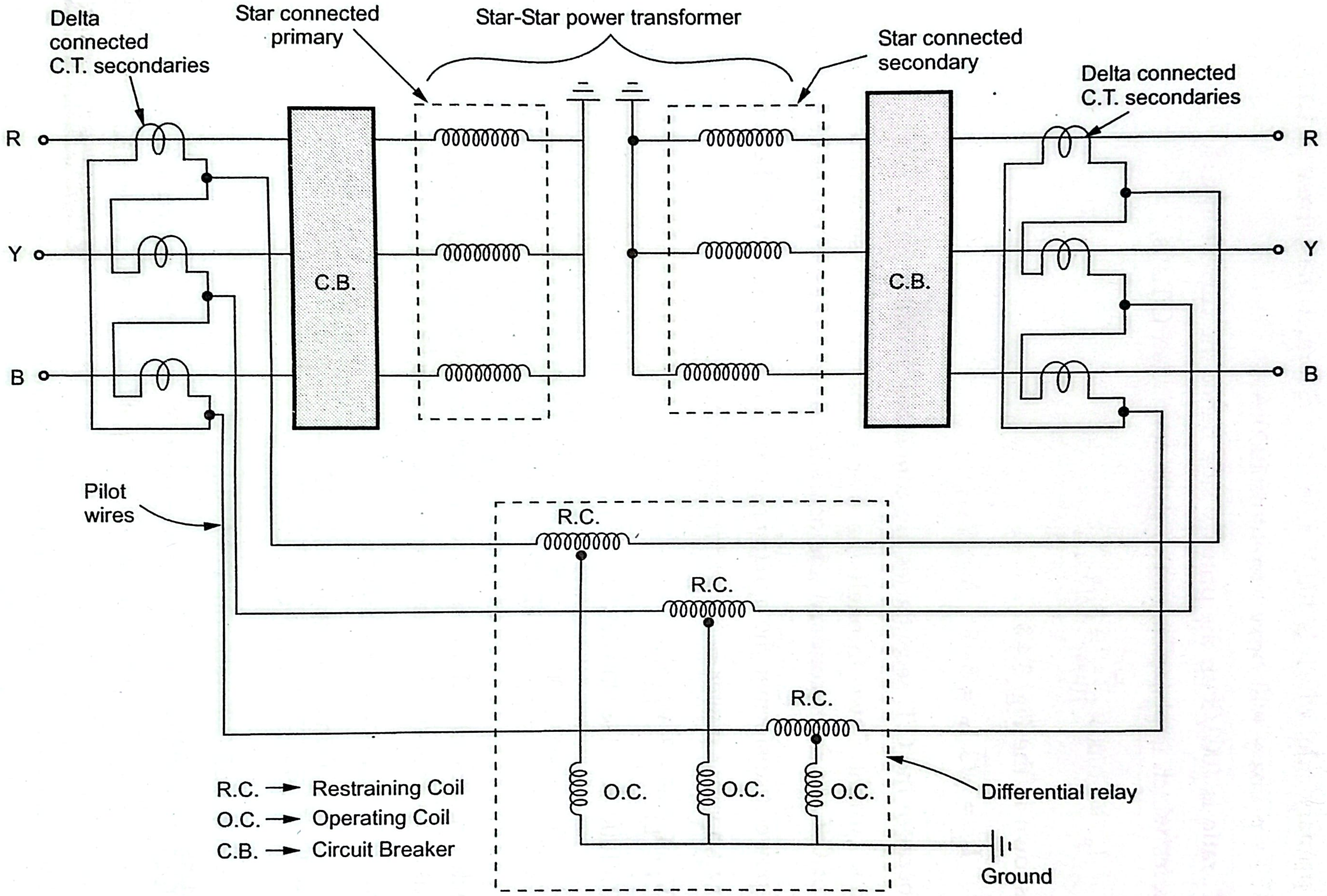

Delta connected C.T. secondaries
Star connected primary
Star-Star power transformer
Star connected secondary
Delta connected C.T. secondaries
R
Y
B
C.B.
C.B.
R
Y
B
Pilot wires
R.C.
R.C.
R.C.
O.C.
O.C.
O.C.
Differential relay
Ground
R.C. → Restraining Coil
O.C. → Operating Coil
C.B. → Circuit Breaker

Fig. 3.4.3 Merz-Price protection for star-star power transformer

Solution : The arrangement is shown in the Fig. 3.4.4.

On the primary side, which is 400 V side of transformer the current is 1000 A.

Hence C.T.s primary will carry current of 1000 A.

The C.T. ratio is 1000/5 on the primary side hence the current in C.T.

Secondaries which is phase current of delta connected C.T.s is,

$$I_P = 1000 \times \frac{5}{1000} = 5\text{ A}$$

This is shown in the Fig. 3.4.4.

$$\therefore \quad I_L = \sqrt{3}\, I_P = 5\sqrt{3}\text{ A}$$

This is because the C.T. secondaries are connected in delta.

The same current flows through the star connected C.T. secondaries. Hence each secondary of C.T. on the secondary side of transformer carries a current of $5\sqrt{3}$ A.

For the power transformer the apparent power on both sides must be same.

$$\therefore \quad \text{Primary apparent power} = \text{Secondary apparent power}$$

$$\therefore \quad \sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2}$$

$$\therefore \quad \sqrt{3} \times 400 \times 1000 = \sqrt{3} \times 33000 \times I_{L2}$$

$$\therefore \quad I_{L2} = \frac{400 \times 1000}{33000} = 12.12\text{ A}$$

Thus each primary of C.T.s connected in star carries a current of 12.12 A while each secondary of C.T.s connected in star carries a current of $5\sqrt{3}$ A.

Hence the C.T. ratio on 33 kV side is,

$$\text{C.T. ratio} = \frac{\text{Primary current}}{\text{Secondary current}} = \frac{12.12}{5\sqrt{3}} = \mathbf{1.4 : 1}$$

This is the required C.T. ratio on 33 kV side.

Example 3.4.2 *A 11 kV/132 kV power transformer is connected in delta-star. The C.T.s on the low voltage side have turns ratio of 600 / 5. Find the suitable turns ratio for the C.T.s on high voltage side.* **AU : Dec.-10, Marks 16**

Solution : The connections are shown in the Fig. 3.4.5.

Let the current on the primary i.e. low voltage side of power transformer be 600 A.

This current will flow through each line on primary of transformer.

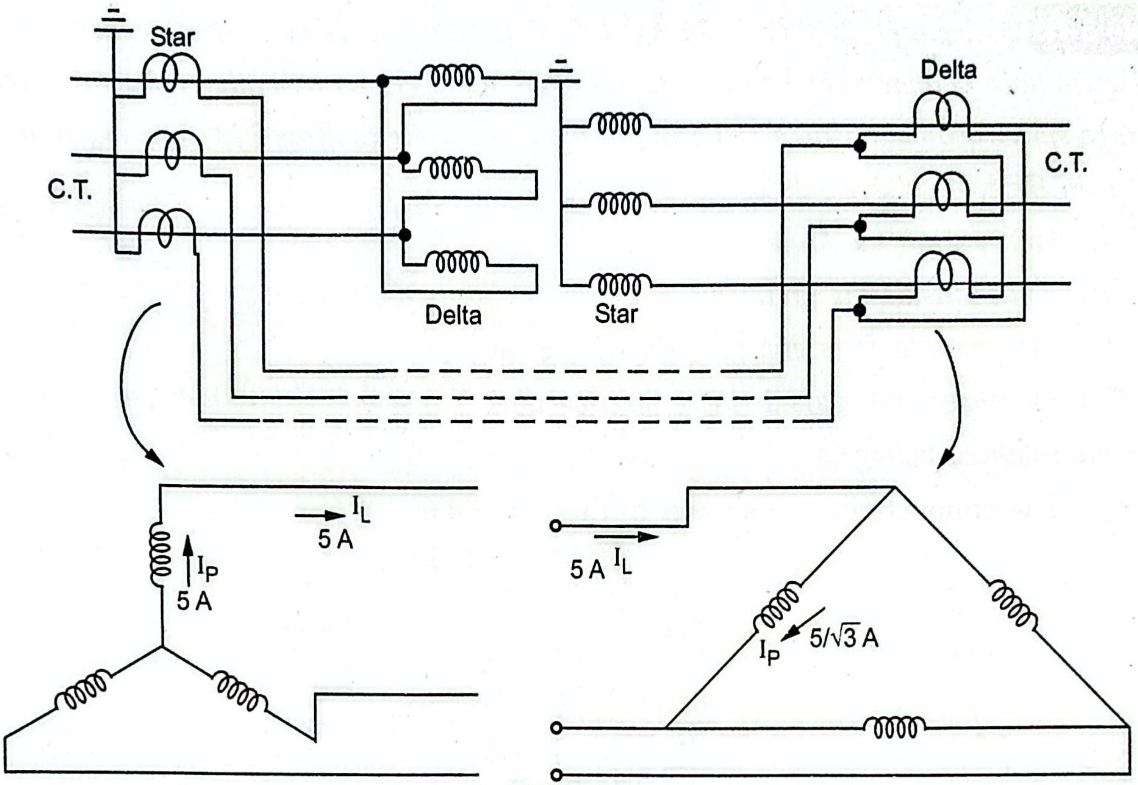


Fig. 3.4.5

Hence current in each secondary of star connected C.T. on primary is the phase current I_P as shown in the Fig. 3.4.5.

$$\therefore \quad I_P = 600 \times \frac{5}{600} = 5 \text{ A}$$

The same in line current I_L which is line current for the C.T.s connected in delta on secondary of transformer.

Hence current in each secondary of C.T. which is phase current of C.T. is $\frac{1}{\sqrt{3}}$ times the line value.

$$\therefore \quad I_P = \frac{5}{\sqrt{3}} \text{ A} \qquad \text{for C. T. secondary connected in delta}$$

Now apparent power on both sides is same.

$$\sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2}$$

$$\therefore \quad \sqrt{3} \times 11000 \times 600 = \sqrt{3} \times 132000 \times I_{L2}$$

$$\therefore \quad I_{L2} = \frac{11000 \times 600}{132000} = 50 \text{ A}$$

This is the current flowing through each primary of delta connected C.T.

$\therefore$ C.T. ratio on high voltage side = $\frac{50}{(5/\sqrt{3})}$ = **17.32 : 1**

Example 3.4.3 *A 3 phase, 200 kVA, 11 kV/400 V transformer is connected in delta-star. The C.T.s on low voltage side have turns ratio of 500/5. Determine the C.T. ratio on high voltage side. Also obtain the circulating current when the fault of 750 A of following types occur on the low voltage side :*

i) Earth fault within the protective zone.

ii) Earth fault outside the protective zone.

iii) Phase to phase fault within the protective zone.

iv) Phase to phase fault outside the protective zone.

Assume balanced voltage.

Solution : The connections are shown in the Fig. 3.4.6.

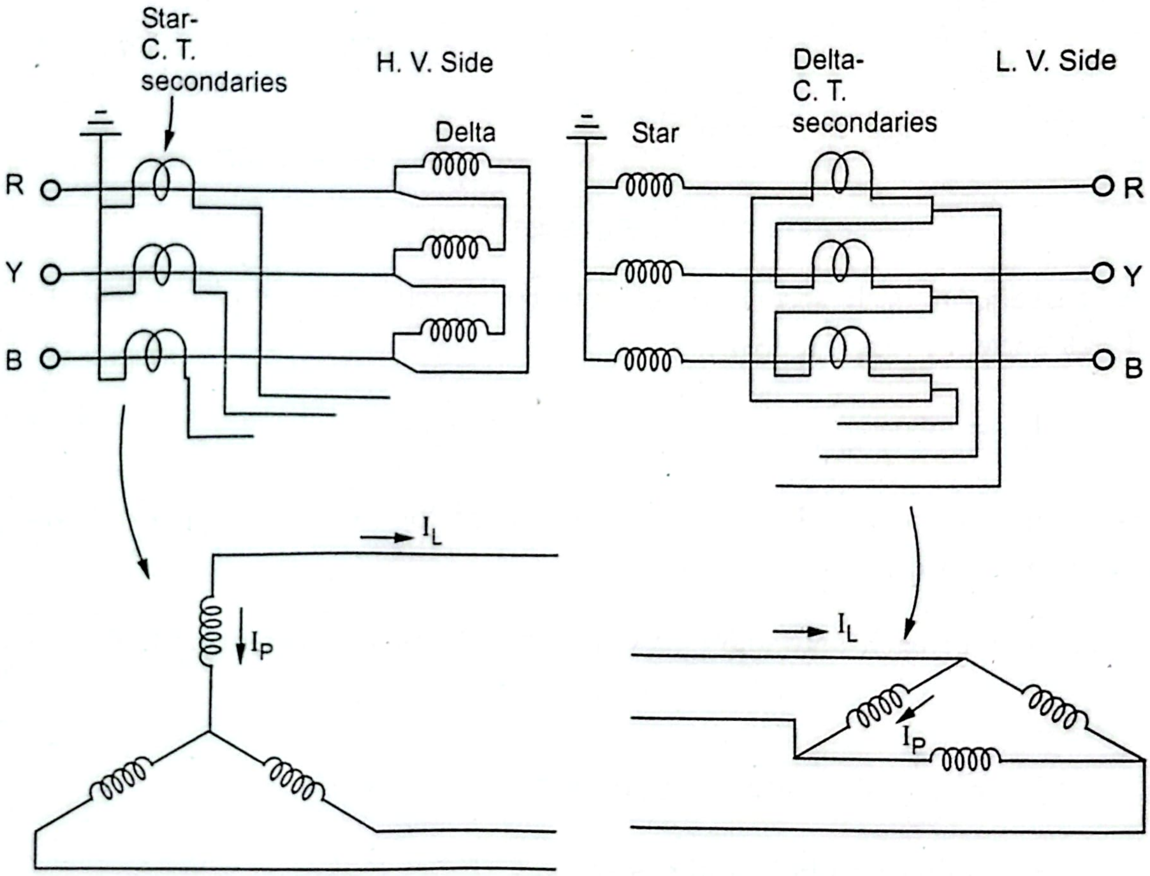


Fig. 3.4.6

On primary which is delta connected, C.T.s are connected in star while

On secondary which is star connected, C.T.s are connected in delta.

Let current on low voltage side be 500 A.

Now $I_{L2} = 500$ A and C.T. ratio 500/5

∴ Current through primary of C.T. on low voltage side = $I_{L2} = 500$ A

∴ I_P = Current through each secondary of delta connected C.T.s

$$= 500 \times \frac{5}{500} = 5 \text{ A}$$

$\therefore$ I_L = Line current through pilot wires = $\sqrt{3}\ I_P = 5\sqrt{3}$ A

Same is the current through each secondary of star connected C.T. on high voltage side.

$\therefore$ $I_P = 5\sqrt{3}$ A on h.v. side C.T. secondaries

Apparent power on both sides of transformers is same.

$$\therefore \quad \sqrt{3}\ V_{L1}\ I_{L1} = \sqrt{3}\ V_{L2}\ I_{L2} \quad \text{i.e} \quad \sqrt{3} \times 11000 \times I_{L1} = \sqrt{3} \times 400 \times 500$$

$$\therefore \quad I_{L1} = \frac{400 \times 500}{11000} = \mathbf{18.18\ A}$$

This is current through each primary of C.T.s connected in star.

$$\therefore \quad \text{Current ratio of C.T.s on high voltage side} = \frac{18.18}{5\sqrt{3}} = \mathbf{2.099 : 1}$$

i) Consider the earth fault within the protective zone as shown in the Fig. 3.4.7.

(See Fig. 3.4.7 on next page.)

Now I_{L2} = 750 A

Equating apparent power,

$$\sqrt{3}\ V_{L1}\ I_{L1} = \sqrt{3}\ V_{L2}\ I_{L2} \quad \text{i.e.} \quad \sqrt{3} \times 11000 \times I_{L1} = \sqrt{3} \times 400 \times 750$$

$$\therefore \quad I_{L1} = \mathbf{27.27\ A}$$

This is the line current on h.v. side under fault condition.

The C.T. ratio is 2.099 : 1. Hence corresponding current through C.T. secondary on h.v. side is, $27.27 \times \frac{1}{2.099}$ = **12.99 A**

So 12.99 A current will flow through the relay and relay will operate.

ii) Consider the earth fault outside the protective zone as shown in the Fig. 3.4.8. The line current on secondary is 750 A.

$$\therefore \quad \text{Secondary C.T. current} = 750 \times \frac{5}{500} = \mathbf{7.5\ A}$$

$\therefore$ Current in pilot wires = $7.5 \times \sqrt{3}$ = **12.99 A** as delta connected

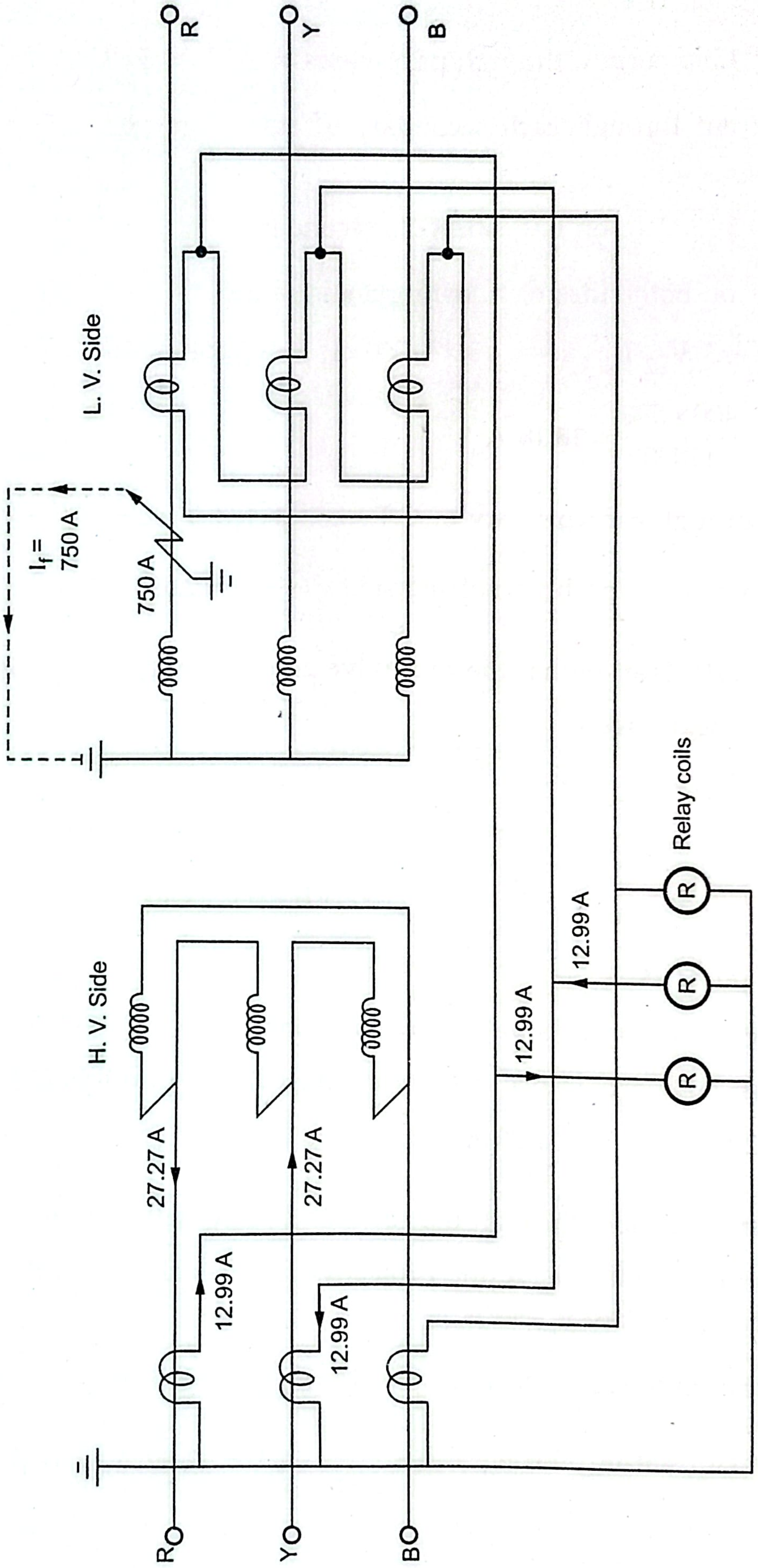

R
Y
B
L. V. Side
H. V. Side
I_f = 750 A
750 A
27.27 A
27.27 A
12.99 A
12.99 A
12.99 A
12.99 A
R
R
R
Relay coils

Fig. 3.4.7

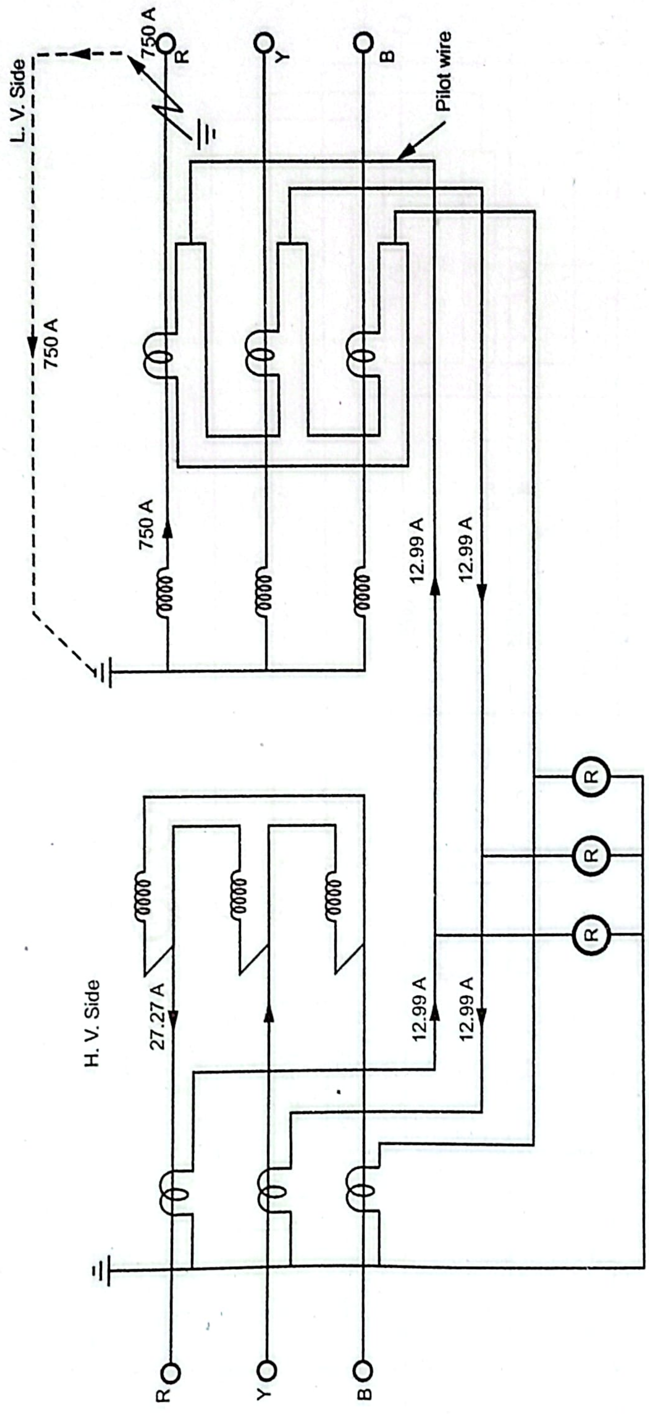

L. V. Side
750 A
750 A
R
Y
B
Pilot wire
750 A
12.99 A
12.99 A
H. V. Side
27.27 A
12.99 A
12.99 A
R
R
R
R
Y
B

Fig. 3.4.8

The currents are shown in the Fig. 3.4.8.

So on both sides the current is balanced hence no current will flow through the relay and **relay will not operate.**

iii) Phase to phase fault in the protected zone on low voltage side. This is shown in the Fig. 3.4.9.

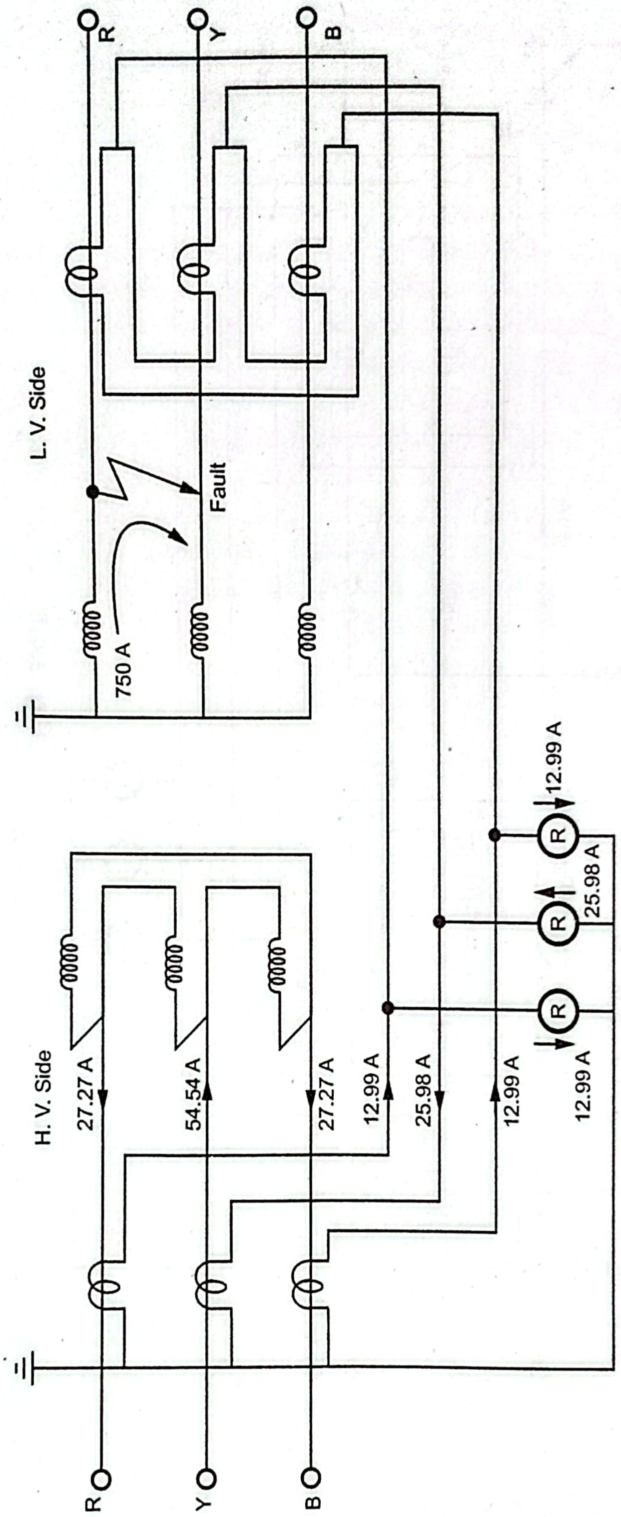

R
Y
B
L. V. Side
Fault
750 A
H. V. Side
27.27 A
54.54 A
27.27 A
12.99 A
25.98 A
12.99 A
12.99 A
R
R
R
25.98 A
12.99 A
R
Y
B

Fig. 3.4.9

Due to such fault current will flow in two phases of low voltage winding but in all three phases in high voltage winding as shown in the Fig. 3.4.9. This current on high voltage side will flow through the relay and **relay will operate.**

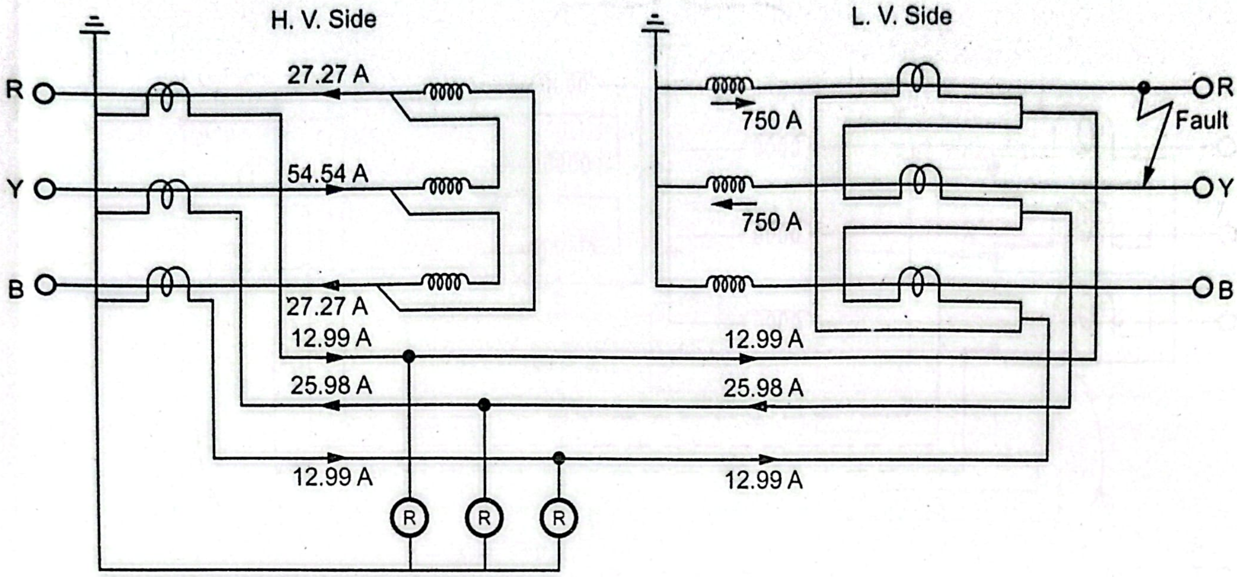


Fig. 3.4.10

iv) Consider phase to phase fault outside the protected zone as shown in the Fig. 3.4.10. The various currents and corresponding distribution is also shown in the Fig. 3.4.10.

As the currents on both sides are balanced, no current flows through the relay hence **relay will not operate.**

Example 3.4.4 *A 3-phase transformer having line voltage ratio of 440 V/11 kV is connected in star/delta. The protection transformer on the LV side have a current ratio of 500/5. What must be the ratio of the protection transformer connected on HV side ?*

AU : April-05, Marks 8

Solution : The arrangement is shown in the Fig. 3.4.11.

On primary side which is 440 V side, let the current be 500 A.

Thus C.T.s will carry the current of 500 A.

The C.T. ratio is 500/5 A hence secondary phase current of C.T.s on primary side is,

$$I_P = \frac{5}{500} \times 500 = 5 \text{ A}$$

$$\therefore \quad I_L = \sqrt{3} \quad I_P = 5\sqrt{3} \text{ A} \qquad \text{... Delta connected C.T.s}$$

The same current flows through the star connected C.T. secondaries. Hence each secondary of C.T. on the secondary side of transformer carries a current of $5\sqrt{3}$ A.

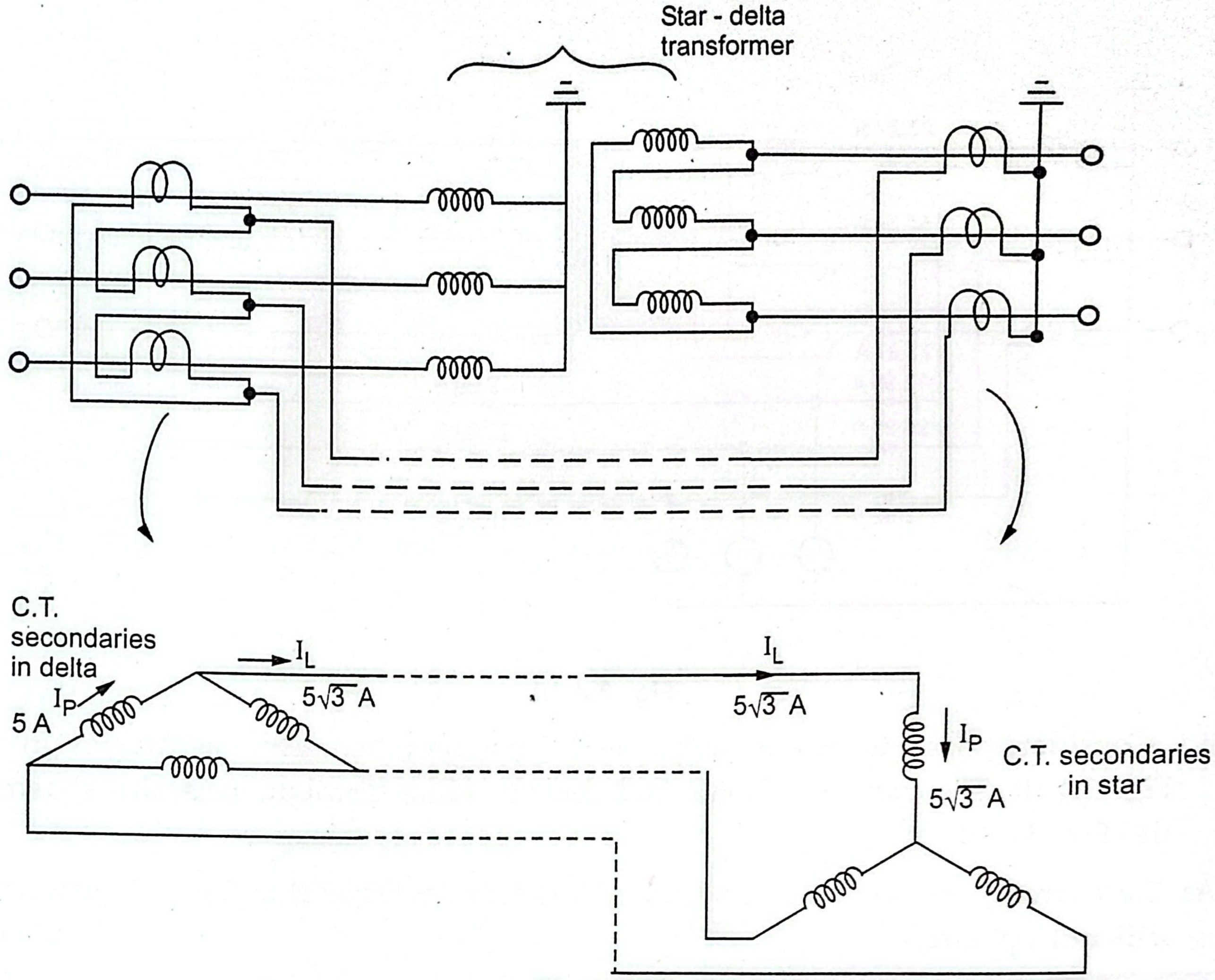

Star - delta
transformer
C.T.
secondaries
in delta
I_P
5 A
I_L
$5\sqrt{3}$ A
I_L
$5\sqrt{3}$ A
I_P
$5\sqrt{3}$ A
C.T. secondaries
in star

Fig. 3.4.11

The apparent power on both sides must be same :

$$\sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2} \quad \text{i.e.} \quad \sqrt{3}\times 440\times 500 = \sqrt{3}\times 11\times 10^3\times I_{L2}$$

$$\therefore \quad I_{L2} = 20 \text{ A}$$

Thus each primary of C.T.s connected in star on H.V. side carries a current of 20 A while each secondary carries current of $5\sqrt{3}$ A.

Hence the C.T. ratio on 11 kV side is,

$$= \frac{\text{Primary current}}{\text{Secondary current}} = \frac{20}{5\sqrt{3}}$$

$$= \mathbf{2.309 : 1} \qquad \text{... Required C.T. ratio on H.V. side}$$

Example 3.4.5 *A 3 phase 500 kVA, 11 kV/0.4 kV transformer is connected in delta/star. The protection transformer on the LV side have turns ratio of 500/5. What will be the C.T. ratio on the HV side of the transformer ?* **AU : Dec.-05, Marks 8**

Solution : The connections are shown in the Fig. 3.4.12

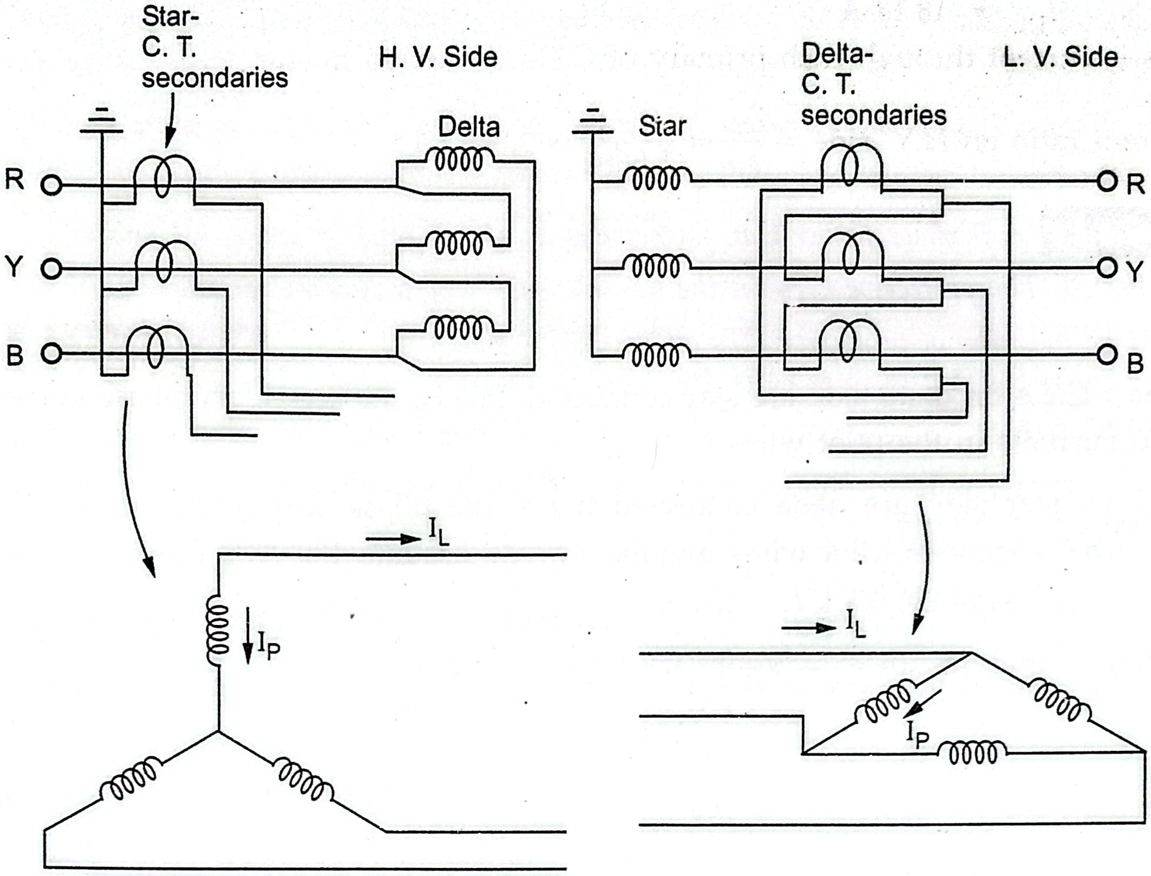

Star-
C. T.
secondaries
H. V. Side
Delta
Star
Delta-
C. T.
secondaries
L. V. Side
R
Y
B
R
Y
B
I_L
I_P
I_L
I_P

Fig. 3.4.12

On primary which is delta connected, C.T.s are in star connection.

On secondary which is star connected, C.T.s are in delta connection.

Let current on low voltage side be 500 A.

i.e. $I_{L2} = 500 \text{ A}$

Current through primary of C.T. on low voltage side = I_{L2} = 500 A

∴ I_P = Current through each secondary of delta connected C.T.s

$$= I_{L2} \times \frac{5}{500} = 500 \times \frac{5}{500} = 5 \text{ A}$$

∴ I_L = Line current through pilot wires.

$$= \sqrt{3}\, I_P = \sqrt{3} \times 5 = 8.6602 \text{ A}$$

Same is the current through each secondary of star conncted C.T. on high voltage side.

∴ I_P = 8.6602 A on H.V. side C.T. secondaries.

Apparent power on both sides of transformer is same.

$\therefore \quad \sqrt{3}\, V_{L1} I_{L1} = \sqrt{3}\, V_{L2} I_{L2}$ i.e. $\sqrt{3}\times 11\times 10^3 \times I_{L1} = \sqrt{3}\times 0.4\times 10^3 \times 500$

$\therefore \quad I_{L1} = \mathbf{18.18\ A}$

This is current through each primary of C.T.s connected in star.

$\therefore$ Current ratio on H.V. side $= \dfrac{I_{L1}}{I_P} = \dfrac{18.18}{8.6602} = \mathbf{2.099 : 1}$

Example 3.4.6 *A 3 phase power transformer has a voltage ratio of 33/6.6 kV and is star-delta connected. The protective CTs on the 6.6. kV side have a current ratio of 100 : 1. What must be the ratio of protective CTs on the 33 kV side ?* **AU : Dec.-07, Marks 6**

Solution : C.T.s on delta side are star connected. Hence the secondary phase currents are equal to currents in the pilot wires.

C.T.s on star side are delta connected hence the phase current in the secondary is equal to the current in pilot wires divided by $\sqrt{3}$. Assume 100 A is flowing in the lines on low voltage side i.e. 6.6 kV.

Primary apparent power = Secondary apparent power

$$\therefore \quad \sqrt{3}\, V_{L1} I_{L1} = \sqrt{3}\, V_{L2} I_{L2}$$

$$\therefore \quad \sqrt{3}\times 33 \times I_{L1} = \sqrt{3}\times 6.6 \times 100$$

$$\therefore \quad I_{L1} = \mathbf{20\ A}$$

This is primary current of C.T. on the high voltage side.

But high voltage side is star connected hence the secondary current on high voltage side is 1 A. Hence the current fed in pilot wires from low voltage side is 1 A. Same current is fed from C.T. connections on high voltage side which are delta connected.

Hence secondary current of C.T.s on high voltage side is $1/\sqrt{3}$ A.

Thus C.T. ratio on high voltage side is $20 : 1/\sqrt{3}$ i.e. $20\sqrt{3} : 1$ i.e. **34.641 : 1.**

Thus the C.T. ratio on high voltage side is **35 : 1**.

Review Questions

1. *Explain the protection scheme used in star/star and star/delta transformers.* **AU : May-04,05,11, Dec.-08,12, Marks 16**
2. *Describe the differential protective scheme for transformer.* **AU : May-14, 17,19, Dec.-13, 17, Marks 16**
3. *Explain the percentage differential protective scheme for transformer. Also tabulate the different types of C.T. connections used for different types of transformer primary and secondary winding connections.* **AU : Dec.-07, Marks 16**

4. *A 3 phase transformer of 220 / 11,000 line volts is connected in star/delta. The protective transformers on 220 V side have a current ratio of 600 / 5. What should be C.T. ratio on 11,000 V side ?* **[Ans. : 1.385 : 1]**
5. *A three phase 66 kV/11 kV power transformer is connected in star/delta. The transformer is protected by Merz-Price circulating current system. Protecting current transformers on the low voltage side have a ratio of 250 / 5. Find the ratio of the current transformers on high voltage side.* **[Ans. : 14.1 : 1]**
6. *A 3 phase, 220 / 11000 V transformer is connected in Y - Δ. The protective transformers on the 220 V sides have a current ratio of 600 / (5 / $\sqrt{3}$). What must be the ratio of the CT's on the 11 kV side and how shall they be ?* **[Ans. : 1.385 : 1]**
7. *Describe with neat block diagram the working of transformer differential protection.*

AU : Dec.-22, Marks 13

3.5 Problems Encountered in Differential Protection

AU : May-04,07,19, Dec.-08,11,15,18

The problems encountered in the simple differential protection are,

1. **Unmatched characteristics of C.T.s :** Though the saturation is avoided, there exists difference in the C.T. characteristics due to ratio error at high values of short circuit currents. This causes an appreciable difference in the secondary currents which can operate the relay. So the relay operates for through external faults.

   This difficulty is overcome by using percentage differential relay. In this relay, the difference in current due to ratio error exists and flows through relay coil. But at the same time the average current ($I_1 + I_2/2$) flows through the restraining coil which produces enough restraining torque. Hence relay becomes inoperative for the through faults.
2. **Ratio change due to tap change :** To alter the voltage and current ratios between high voltage and low voltage sides of a power transformer, a tap changing equipment is used. This is an important feature of a power transformer. This equipment effectively alters the turns ratio. This causes unbalance on both sides. To compensate for this effect, the tappings can be provided on C.T.s also which are to be varied similar to the main power transformer. But this method is not practicable.

   The percentage differential relays ensure the stability with respect to the amount of unbalance occurring at the extremities of the tap change range.
3. **Difference in lengths of pilot wires :** Due to the difference in lengths of the pilot wires on both sides, the unbalance condition may result. The difficulty is overcome by connecting the adjustable resistors in pilot wires on both sides. These are called balancing resistors. With the help of these resistors equipotential points

on the pilot wires can be adjusted. In percentage differential relays the taps are provided on the operating coil and restraining coil to achieve balance.

4. **Magnetizing current inrush :** When the transformer is energized, the condition initially is of zero induced e.m.f. and it is similar to the switching of an inductive circuit. Due to this the transient inrush of magnetising current flows in to the transformer. This current is called magnetizing current inrush. This current may be as great as 10 times the full load current of the transformer. This decays very slowly and is bound to operate differential protection of the transformer falsely.

   The factors which affect the magnitude and direction of the magnetizing current inrush are,

a. Size of the transformer.
b. Size of the power system.
c. Type of magnetic material used for the core.
d. The amount of residual flux existing before energizing the transformer.
e. The method by which transformer is energized.

If the transformer is energized when the voltage wave is passing through zero, the magnetizing current inrush is maximum. At this instant, the current and flux should be maximum in highly inductive circuit. And in a half wave flux reversal must take place to attain maximum value in the other half cycles. If the residual flux exists, the required flux may be in same or opposite direction. Due to this magnetizing current inrush is less or more. If it is more, it is responsible to saturate the core which further increases its component.

This current decays rapidly for first few cycles and then decays slowly. The time constant L/R of the circuit is variable as inductance of circuit varies due to the change in permeability of the core. The losses in the circuit damp the inrush currents. Depending on the size of the transformer, the time constant of inrush current varies from 0.2 sec to 1 sec.

The waveforms of magnetizing inrush current in three phases is shown in the Fig. 3.5.1.

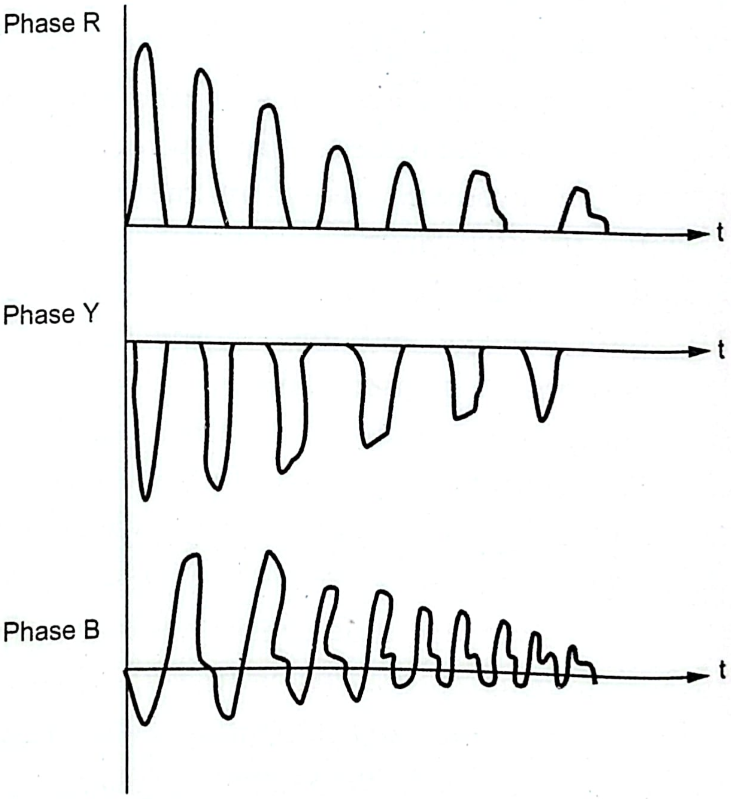


Fig. 3.5.1 Typical magnetizing inrush current waveforms

There are number of ways ensuring immunity from the operation by magnetizing surges. Firstly the relay may be given a setting higher than maximum inrush current. Secondly the time setting may be made long enough for the magnetizing current to fall to a value below the primary operating current before the relay operates. But these simple remedies are inconsistent with high speed and low primary operating current.

In the latest method, the harmonic content of the magnetizing current flowing in the operating circuit is filtered out and passed through a restraining coil. This is called harmonic current restraint.

3.5.1 Harmonic Restraint and Harmonic Blocking

The high initial inrush of magnetizing currents consist of a high component of even and odd harmonics.

Table 3.5.1 gives the typical values of harmonic contents in a magnetizing current.

Order of harmonic content in magnetizing current	Amplitude as a % of fundamental component
2nd	63.0
3rd	26.8
4th	5.1
5th	4.1
6th	3.7
7th	2.4

Table 3.5.1

The operating coil carries the fundamental component of the inrush current only. The harmonic contents and fundamental together is passed through the restraining coil.

Thus more the harmonic contents in the inrush current, more is the restraining torque and the relay does not operate. So use of percentage differential protection rather than simple differential protection is preferred. The circuit used to compensate the effect of magnetizing current using harmonic restraint method is shown in the Fig. 3.5.2.

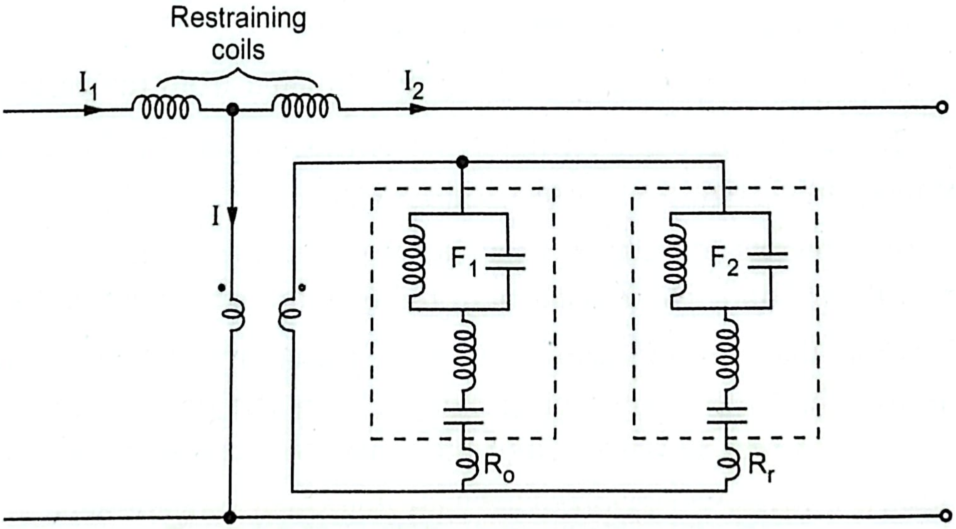


Fig. 3.5.2 Magnetizing current compensation

The filter F_1 is designed to pass the fundamental 50 Hz component which excites the operating coil R_o. The magnetizing current has large third harmonic component. There is an additional restraining coil R_r. The filter F_2 is designed to pass the third harmonic component which energizes the additional restraining coil R_r. The current passing through normal restraining coil and current passing through additional restraining coil R_r produce sufficient restraining torque. This compensates for the differential current resulting due to the flow of magnetizing current.

The separate blocking relay in series with the differential relay is used. The operation of this relay is based on harmonic component of inrush current. This relay consists of 100 Hz blocking filter in operating coil while 50 Hz filter in restraining coil. At the time of inrush current, second harmonic component is maximum and thus blocking relay is blocked with its contacts remain open.

In short circuit case, the harmonic component is negligible and 50 Hz component is dominant. Hence the blocking relay operates to close its contact. This principle is called **harmonic blocking**.

Review Questions

1. *Explain the factors causing difficulty in applying Merz-Price circulating current principle to a power transformer and how are they overcome.* **AU : May-04,07,19, Dec.-08, 11, Marks 8**
2. *With the basic circuit diagram, explain harmonic restraint relay protection for a transformer.* **AU : Dec.-15, Marks 8**
3. *Explain how a transformer can be protected against magnetizing inrush current. Illustrate with suitable diagram.* **AU : Dec.-18, May-19, Marks 13**

3.6 Frame Leakage Protection

AU : May-19

This protection is nothing but the method of providing earth fault protection to the transformer. This protection can be provided to the metal clad switchgear.

The arrangement is shown in the Fig. 3.6.1.

The metal clad switchgear is lightly insulated from the earth.

The frame of the switchgear i.e. enclosure is grounded. This is done through a primary of current transformer in between.

The concrete foundation of switchgear and the other equipments are lightly insulated from the ground. The resistance of these equipments with earth is about 12 ohms.

When there is an earth fault, then fault current leaks from the frame and passes through the earth connection provided. Thus the primary of C.T. senses the current due to which current passes through the sensitive earth fault relay. This operates the relay.

Such a protection is provided only for small transformers. For the large transformers, the differential protection is enough to sense and operate for the earth faults.

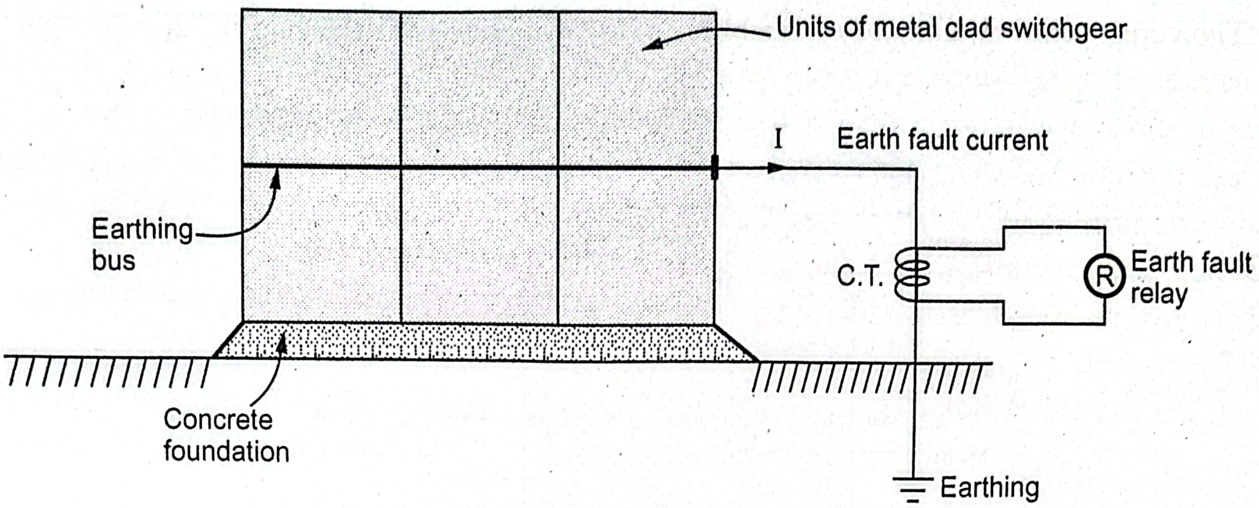

Units of metal clad switchgear
I
Earth fault current
Earthing bus
C.T.
R
Earth fault relay
Concrete foundation
Earthing

Fig. 3.6.1 Frame leakage protection

Review Question

1. *Explain the frame leakage protection for transformer.* **AU : May-19, Marks 4**

3.7 Buchholz Relay (Incipient Fault Protection)

AU : Dec.-04,14,16, May-06,13,18,19

The Buchholz relay is a gas operated relay used for the protection of oil immersed transformers against all the types of internal faults. It is named after its inventor, Buchholz. The slow developing faults called **incipient faults** in the transformer tank below oil level operate Buchholz relay which gives an alarm. If the faults are severe it disconnects the transformer from the supply.

It uses the principle that due to the faults, oil in the tank decomposes, generating the gases. The 70 % component of such gases is hydrogen which is light and hence rises upwards towards conservator through the pipe. Buchholz relay is connected in the pipe, as shown in the Fig. 3.7.1 Due to the gas collected in the upper portion of the Buchholz relay, the relay operates and gives an alarm.

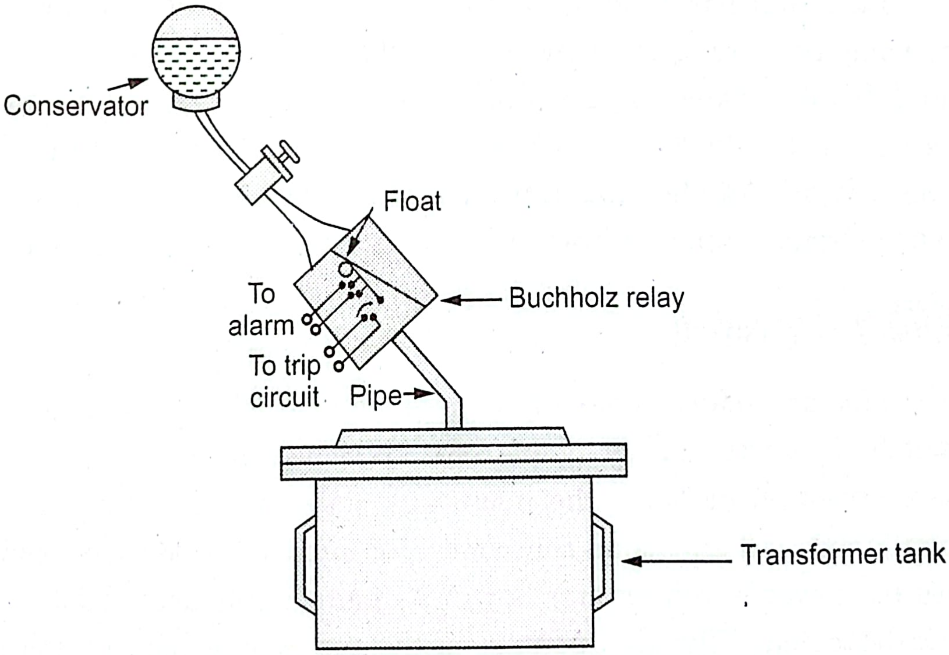

Conservator
Float
To alarm
Buchholz relay
To trip circuit
Pipe
Transformer tank

Fig. 3.7.1 Basic arrangement of Buchholz relay

The constructional features of Buchholz relay are shown in the Fig. 3.7.2.

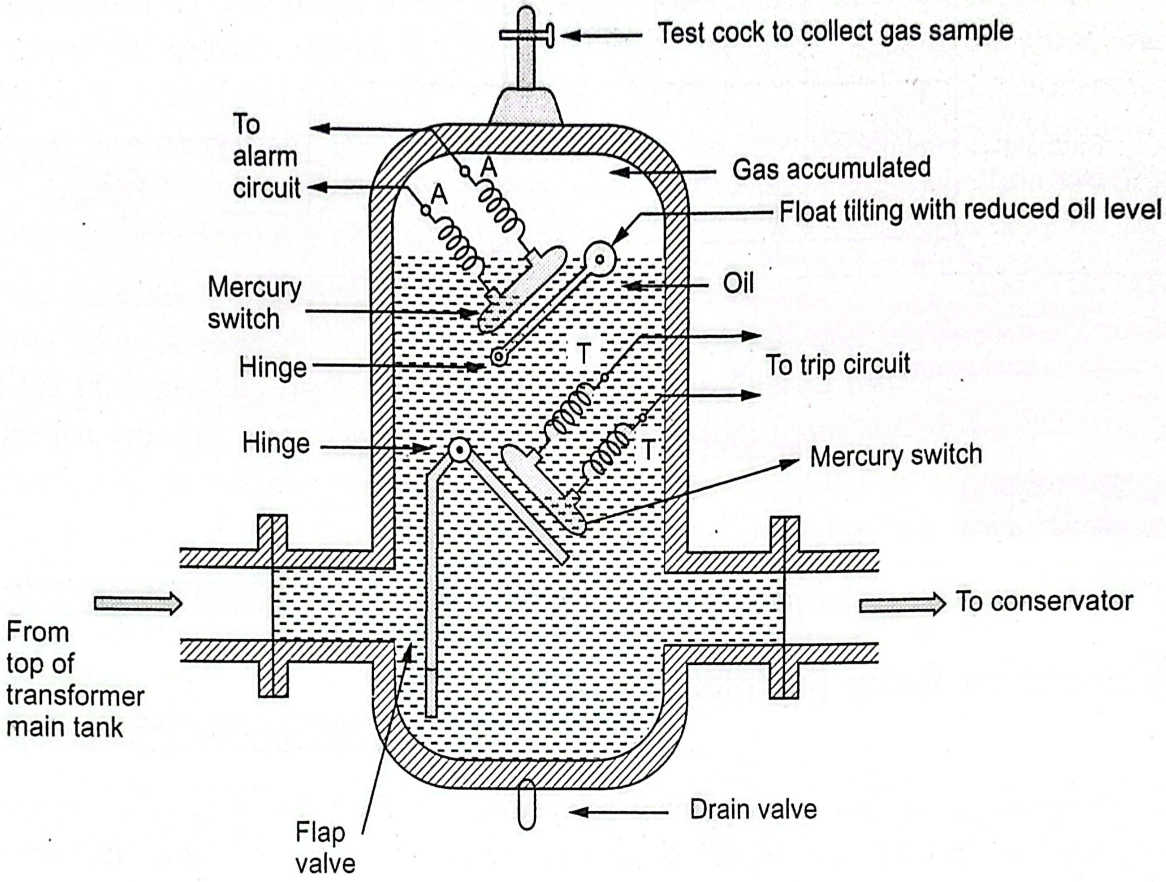

Test cock to collect gas sample
To alarm circuit
A
A
Gas accumulated
Float tilting with reduced oil level
Mercury switch
Oil
Hinge
T
To trip circuit
Hinge
T
Mercury switch
From top of transformer main tank
To conservator
Drain valve
Flap valve

Fig. 3.7.2 Construction of Buchholz relay

Under normal conditions, the Buchholz relay is full of oil. It consists of a cast housing containing a hinged hollow float. A mercury switch is attached to a float. The float being rotated in the upper part of the housing. Another hinged flap valve is located in the lower part which is directly in the path of the oil between tank and the conservator. Another mercury switch is attached to a flap valve. The float closes the alarm circuit while the lower flap valve closes the trip circuit in case of internal fault.

3.7.1 Operation

There are many types of internal faults such as insulation fault, core heating, bad switch contacts, faulty joints etc. which can occur. When the fault occurs the decomposition of oil in the main tank starts due to which the gases are generated. As mentioned earlier, major component of such gases is hydrogen. The hydrogen tries to rise up towards conservator but in its path it gets accumulated in the upper part of the Buchholz relay. Through passage of the gas is prevented by the flap valve.

When gas gets accumulated in the upper part of housing, The oil level inside the housing falls. Due to which the hollow float tilts and close the contacts of the mercury switch attached to it. This completes the alarm circuit to sound an alarm. Due to this operator knows that there is some incipient fault in the transformer. The transformer is disconnected and the gas sample is tested. The testing results give the indication, what type of fault is started developing in the transformer. Hence transformer can be disconnected before fault grows into a serious one. The alarm circuit does not immediately disconnects the transformer but gives only indication to the operator. This is because some times bubbles in the oil circulating system may operate the alarm circuit though actually there is no fault.

However if a serious fault such as internal short circuit between phases, earth fault inside the tank etc. occurs then the considerable amount of gas gets generated. Thus due to fast reduce level of oil, the pressure in the tank increases. Due to this the oil rushes towards the conservator. While doing so it passes though the relay where flap valve is present. The flap valve gets deflected due to the rushing oil. Due to this the mercury switch contacts get closed. This energizes the trip circuit which opens the circuit breaker. Thus transformer is totally disconnected from the supply.

The connecting pipe between the tank and the conservator should be as straight as possible and should slope upwards conservator at a small angle from the horizontal. This angle should be between 10 to 11°.

For the economic considerations, Buchholz relays are not provided for the transformers having rating below 500 kVA.

3.7.2 Advantages

The various advantages of the Buchholz relay are,

1. Normally a protective relay does not indicate the appearance of the fault. It operates when fault occurs. But Buchholz relay gives an indication of the fault at very early stage, by anticipating the fault and operating the alarm circuit. Thus the transformer can be taken out of service before any type of serious damage occurs.
2. It is the simplest protection in case of transformers.

3.7.3 Limitations

The various limitations of the Buchholz relay are,

1. Can be used only for oil immersed transformers having conservator tanks.
2. Only faults below oil level are detected.
3. Setting of the mercury switches can not be kept too sensitive otherwise the relay can operate due to bubbles, vibration, earthquakes mechanical shocks etc.

4. The relay is slow to operate having minimum operating time of 0.1 seconds and average time of 0.2 seconds.

3.7.4 Applications

The following types of **transformer** faults can be protected by the Buchholz relay and are indicated by alarm :

1. Local overheating
2. Entrance of air bubbles in oil
3. Core bolt insulation failure
4. Short circuited laminations
5. Loss of oil and reduction in oil level due to leakage
6. Bad and loose electrical contacts
7. Short circuit between phases
8. Winding short circuit
9. Bushing puncture
10. Winding earth faults.

Review Questions

1. *Describe the construction and working of Buchholz relay.* **AU : Dec.-04, May-06, 13, Marks 8**
2. *Mention the advantages, limitations and applications of Buchholz relay.*
3. *Briefly discuss the protective devices used for the protection of a large transformer.* **AU : Dec.-14, May-19, Marks 8**
4. *Explain a protection scheme for protection of transformer against incipient fault.* **AU : Dec.-16, May-18, Marks 8**

3.8 Two Marks Questions with Answers

Q.1 What are the possible faults in transformers ? **AU : Dec.-08,22**

Ans. :
1. Overheating due to overloads and short circuits.
2. Winding faults such as phase to phase, earth fault and interturn fault.
3. Open circuits.
4. Through faults occurring outside the protected zone.
5. Overfluxing due to high V/f ratio.
6. Other faults such as tap-changer faults, high voltage surges, incipient faults etc.

Q.2 What are the main safety devices available with transformers ? **AU : May-12**

Ans. : Buchholz's relay, differential protection scheme, oil level gauge, sudden pressure delay, oil temperature indicator, winding temperature indicator.

Q.3 State the advantages of Buchholz's relay.

Ans. : 1. It gives an indication of the fault at early stage, operating the alarm system.

2. It is simplest protection in case of transformers.

3. It is specially sensitive to interturn faults.

4. Its operation and handling is very easy.

Q.4 List out the limitations of Buchholz's relay. **AU : May-17**

Ans. : 1. Can be used only for oil immersed transformers.

2. Faults only below the oil level are detected.

3. Setting of the mercury switches cannot be kept too sensitive otherwise relay can operate due to bubbles, vibration etc.

4. It is slow to operate.

Q.5 Mention the faults which can be protected using Buchholz's relay. **AU : Dec.-22**

Ans. : 1. Local overheating. 2. Entrance of air bubbles in oil.

3. Core bolt insulation failure. 4. Short circuited laminations.

5. Reduction of oil level due to leakage. 6. Bad and loose electrical contacts.

7. Short circuit between phases and windings. 8. Bushing puncture.

Q.6 What are the problems encountered in simple differential protection of transformers ? **AU : Dec.-15, May-17**

OR What are the factors affecting the performance of differential relays ? **AU : Dec.-18**

Ans. : 1. Unmatched characteristics of C.T.s which can cause appreciable difference in the secondary currents which can operate the relay.

2. Ratio change due to tap change.

3. Difference in lengths of pilot wires which can cause unbalance conditions.

4. Magnetizing current inrush at the time of switching of transformer which can operate the relay falsely.

Q.7 Mention the factors affecting the magnitude and direction of the magnetizing current inrush in transformers.

Ans. : 1. Size of the transformer. 2. Size of the power system.

3. Type of the magnetic material used for the core.

4. Amount of residual flux existing in the core.

5. Method used to energize the transformer.

Q.8 How C.T.s are connected while protecting transformers ? Why ?

Ans. : In case of transformers there is an inherent phase difference between the voltages induced in high voltage winding and low voltage winding. Due to this there exists phase difference between the C.T. secondary currents on two sides of a transformer. A differential current may result due to such phase difference which may operate the relay. To compensate for such a phase difference, the C.T.s are connected in such a way that the secondaries of C.T.s on star connected side of a transformer are connected in delta while the secondaries of C.T.s on delta connected side of a transformer are connected in star.

Q.9 For the Merz-price circulating current system for the protection of a 1000 kVA, 11 kV/400 V delta-star 3 phase transformer, find the turns ratio of the current transformers for a nominal 5 A secondary current. **AU : May-06**

Ans. : On primary which is delta connected, C.T.s are connected in star while on secondary which is star connected, C.T.s are connected in delta.

The line current through secondaries of C.T. is 5 A. Hence, the phase current is $5/\sqrt{3}$ A.

Let the C.T. ratio of delta connected C.T.s on secondary be $(100 : 5/\sqrt{3})$.

Thus the line current through primary of C.T. is 100 A.

$$\therefore \quad I_{L2} = 100 \text{ A} \qquad \text{... line current on low voltage side}$$

Apparent power on both sides of transformers is same.

$$\therefore \quad \sqrt{3}\, V_{L1}\, I_{L1} = \sqrt{3}\, V_{L2}\, I_{L2} \quad \text{i.e.} \quad \sqrt{3}\times 11\times 10^3 \times I_{L1} = \sqrt{3}\times 400\times 100$$

$$\therefore \quad I_{L1} = \frac{40}{11} \text{ A}$$

This is current through each primary of C.T.s. connected in star on high voltage side. While the secondary of C.T.s connected in star carry the current of 5 A.

$$\therefore \quad \text{Current ratio of C.T.s on high voltage side} = \frac{40}{11} : 5$$

Q.10 Mention the differences between the current transformers used for protection and measurement. **AU : May-05**

Ans. : The measuring C.T.s require high accuracy over the range of 10 % to 120 % of rated current. It is better if C.T. saturates for currents exceeding this range. The protection C.T.s require linear characteristics upto secondary voltage corresponding to maximum fault current. The core of protective C.T. is of larger cross-section. The materials like grain oriented steels having high saturation levels are used for protection C.T.s while nickel-iron alloys having low exciting ampere-turns per unit length of core are used for measuring C.T.s.

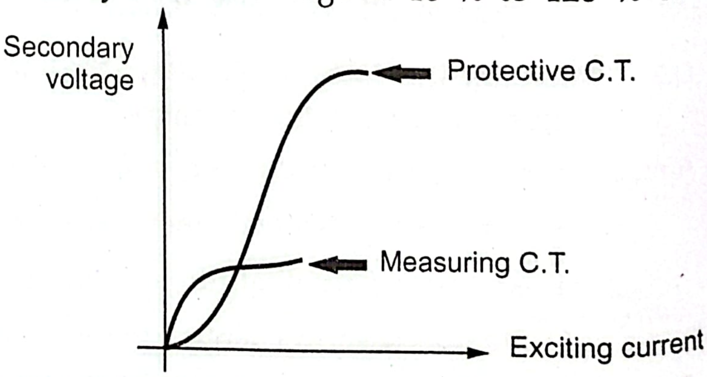


Fig. 3.8.1 Difference between protective and measuring C.T.

Q.11 What is the meaning of burden on C.T. ? **AU : Dec.-06**

Ans. : The **burden on C.T.** is defined as the load connected across its secondary, which is usually expressed in Volt Amperes (VA). It can also be expressed in terms of impedance at the rated secondary current at a given power factor.

Q.12 What are the applications of C.T.s and P.T.s in a power system ? **AU : May-14, Dec.-07**

Ans. : 1. To sense the current in circulating current differential protection

2. In over current phase fault protection. 3. In various types of distance protection.

4. Intermediate C.T.s for feeding protective devices, measuring systems, relays etc.

Q.13 Why the secondary of C.T. should not be open ? **AU : Dec.-11, 14, 17, May-15**

Ans. : If the secondary of C.T. is kept open then current through secondary becomes zero hence the ampere turns produced by secondary which generally oppose primary ampere turns becomes zero. As there is no counter m.m.f., unopposed primary m.m.f. produce high flux in the core. This produces excessive core loss heating the core. It also produces heavy e.m.f. on primary and secondary side which may damage the insulation of the winding. This is dangerous from the operator point of view as well. Hence the secondary of C.T. should not be open.

Q.14 Define ratio error for instrument transformers.

Ans. : Practically transformation ratio of transformers depends on load current, power factor and exciting current. Due to this large error is introduced in the measurement which is called ratio error. The ratio error is defined as,

$$\% \text{ Ratio error} = \frac{K_n - R}{R} \times 100$$

$$\text{Where } K_n = \text{Nominal ratio} = \frac{\text{Rated primary current}}{\text{Rated secondary current}} \quad \text{... For C.T.}$$

$$= \frac{\text{Rated primary voltage}}{\text{Rated secondary voltage}} \quad \text{... For P.T.}$$

$$R = \text{Actual ratio} = \frac{\text{Actual primary current}}{\text{Actual secondary current}} \quad \text{... For C.T.}$$

$$= \frac{\text{Actual primary voltage}}{\text{Actual secondary voltage}} \quad \text{... For P.T.}$$

Q.15 State the formula to calculate ratio error for instrument transformers.

Ans. : The formula to calculate ratio error is,

$$\boxed{R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_2}}$$

Where n = Turns ratio, I_2 = Secondary current

I_m = Magnetising component of exciting current

I_c = Loss or active component of exciting current

δ = Angle between secondary induced voltage and I_2 δ is positive for lagging p.f. and negative for leading p.f.

Q.16 What is phase angle error for instrument transformers ?

Ans. : In the power measurements, it is must that the phase of secondary current is to be displaced by exactly 180° from that of primary current for C.T. While the phase of secondary voltage is to be displaced by exactly 180° from that of primary voltage, for P.T. But actually it is not so. The error introduced due to this fact is called phase angle error. It denoted by angle θ by which the phase difference between primary and secondary is different from 180°.

Q.17 What is over fluxing ? How it affect transformer ? **AU : Dec.-16**

Ans. : Practically transformers are operated with a flux density which is close to its saturation value. If practically transformer voltage increases beyond rated value with constant frequency then flux in the core increases which increases flux density to such a value at which transformer gets driven into deep saturation. This phenomenon is called over fluxing. Due to over fluxing, transformer draws very high magnetizing current, large eddy currents get induced in the structural parts, large increase in core losses, due to which over heating of the core occurs. It also weaknes the insulation of winding and mechanical supports. The contamination of the transformer coil may result due to over fluxing. Hence over fluxing must be avoided.

Q.18 What is the need for instrument transformer ? **AU : May-17**

Ans. : When the voltages and currents are very high in a.c. circuits then measurement can not be done by using method of extension of ranges of low range meters. For measurement of such high voltages and currents, specially constructed accurate ratio transformers are required which are called instrument transformers. They isolate the instruments from high current and high voltage a.c. circuits.

Q.19 What are the errors in CT ? **AU : May-19**

Ans. : The two possible errors in CT are, i) Ratio error and ii) Phase angle error

Refer Q.14 and Q.16 for details of these errors.

3.9 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *Explain a protection scheme for protection of transformer against incipient fault.* **[Section 3.7]** **[8]**

May-17

Q.2 *Give a detailed explanation for protection of transformer using differential protection which includes associated faults.* **[Section 3.4]** **[16]**

Q.3 *Give a detailed explanation about CT's and PT's and its application to power system.* **[Section 3.1]** **[16]**

Dec.-17

Q.4 *Give a brief account on the faults and protection of transformers.* **[Sections 3.3 and 3.4]** **[16]**

May-18

Q.5 *Explain clearly about Buchholz relay for the protection of incipient faults in transformers.* **[Section 3.7]** **[10]**

Dec.-18

Q.6 *Explain how a transformer can be projected against magnetizing inrush current. Illustrate with suitable diagram.* **[Section 3.5]** **[7]**

May-19

Q.7 *Describe the various methods of transformer protection.* **[Sections 3.4, 3.6 and 3.7]** **[7]**

Q.8 *With a neat sketch, explain the differential system of protection applied to star delta connected transformer.* **[Section 3.4]** **[8]**

Q.9 *What are the problems arising in differential protection in power transformer and how are they overcome ?* **[Section 3.5]** **[7]**

(Regulation 2017)

Dec.-22

Q.10 *Describe with neat block diagram the working of transformer differential protection.* **[Section 3.4]** **[13]**

❑❑❑

UNIT III

4

Generator and Motor Protection

Syllabus

Protection of generator and motors.

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4.6 Restricted Earth Fault Protection of Generator ***Dec.-04,05,06,08,16,18,22,***
. . . . ***April-05, May-06,07,11,12,18,*** *Marks 16*
4.7 Unrestricted Earth Fault Protection . . . . ***May-05,*** · · · · · · · · · · · · · · · *Marks 8*
4.8 Balanced Earth Fault Protection
4.9 100 % Earth Fault Protection
4.10 Stator Protection against Interturn Faults . . . . . ***May-12, 15, Dec.-12,*** · · · · *Marks 16*
4.11 Rotor Earth Fault Protection
4.12 Protection against Loss of Excitation (Field Failure)
. . . . ***May-08,22, Dec.-12,*** · · · · · *Marks 16*
4.13 Detection of Turn-Turn Fault
4.14 Negative Sequence Protection . . . . ***May-04,*** · · · · · · · · · · · · · · · *Marks 8*
4.15 Reverse Power Protection (Loss of Prime Mover Protection)
4.16 Introduction to Motor Protection
4.17 Abnormal Conditions and Failure in Case of Induction Motor
4.18 Protection Circuit for Induction Motor . . . . ***Dec.-06,16,22, May-18,*** · · · · *Marks 8*
4.19 Single Phasing Preventer
4.20 Ground Fault Protection
4.21 Phase Fault Protection
4.22 Phase Reversal Protection
4.23 Two Marks Questions with Answers
4.24 University Questions with Answers (Long Answered Questions)

4.1 Introduction

The generators used in the power system are the alternators which produce very high a.c. voltages. The protection of generators is very much complex due to the following reasons,

1. The generators are very large machines producing very high voltages and are connected to busbars.
2. Various other equipments are always associated with the generators. Such equipments are prime movers, excitation systems, voltage regulators, cooling systems etc. Thus protection of generators must consider the presence of these other equipments also.
3. The generators are very costly, expensive and very important factor in a power system. The protection scheme must be such that it should not shut off the generators as far as possible. The shut off generators result in a power shortage.

All these factors make the design of protection scheme for the generator, very much complex.

Before studying the various protection schemes for the generators, let us discuss various faults which can occur associated with the generators.

Review Question

1. *Why the protection of generators is very much complex ?*

4.2 Generator Faults

AU : Dec.-06,22, May-07

The various faults which can occur associated with a generator can be classified as,

1. **Stator faults :** The faults associated with the stator of the generator.
2. **Rotor faults :** The faults associated with the rotor of the generator.
3. **Abnormal running conditions :** This includes number of abnormal conditions which may occur in practice, from which the generator must be protected.

Let us discuss these faults in detail.

4.2.1 Stator Faults

The stator faults means faults associated with the three phase armature windings of the generator. These faults are mainly due to the insulation failure of the armature windings. The main types of stator faults are,

1. Phase to earth faults 2. Phase to phase faults

3. Inter-turn faults involving turns of same phase winding.

The most important and common fault is phase to earth fault. The other two are not very common while inter-turn fault is very difficult to detect.

4.2.1.1 Phase to Earth Faults

These faults mainly occur in the armature slots. The faults are dangerous and can cause severe damage to the expensive machine. The fault currents less than 20 A cause negligible burning of core if machine is tripped quickly. But if the fault currents are high, severe burning of stator core can take place. This may lead to the requirement of replacing the laminations which is very costly and time consuming. So to avoid the damage due to phase to earth faults, a separate, sensitive earth fault protection is necessary for the generators alongwith the earthing resistance.

4.2.1.2 Phase to Phase Faults

The phase to phase faults means short circuit between two phase windings. Such faults are uncommon because the insulation used between the coils of different phases in a slot is large. But once phase to earth fault occurs, due to the over heating phase to phase fault also may occur. This fault is likely to occur at the end connections of the armature windings which are overheating parts outside the slots. Such a fault causes severe arcing with very high temperatures. This may lead to melting of copper and fire if the insulation is not fire resistant.

4.2.1.3 Stator Inter-Turn Faults

The coils used in the alternators are generally multiturn coils. So short circuit between the turns of one coil may occur which is called an inter-turn fault. This fault occurs due to current surges with high value of (L di/dt) voltage across the turns. But if the coils used are single turn then this fault can not occur. Hence for the large machines of the order of 50 MVA and more, it is a normal practice to use single turn coils. But in some countries, multiturn coils are very commonly used where protection against inter-turn faults is must.

4.2.2 Rotor Faults

The rotor of an alternator is generally a field winding as most of the alternators are of rotating field type. The field winding is made up of number of turns. So the conductor to earth faults and short circuit between the turns of the field winding, are the commonly occurring faults with respect to a rotor. These faults are caused due to the severe mechanical and thermal stresses, acting on the field winding insulation.

The field winding is generally not grounded and hence single line to ground fault does not give any fault current. A second fault to earth will short circuit the part of the field winding and may there by produce an unsymmetrical field system. Such an unsymmetrical system gives rise to the unbalanced forces on the rotor and results in excess pressure on the bearings and the shaft distortion, if such a fault is not cleared very early. So it is very much necessary to know the existence of the first occurrence of the earth fault so that corrective measures can be taken before second fault occurs.

The unbalanced loading on the generator is responsible to produce the negative sequence currents. These currents produce a rotating magnetic field which rotates in opposite direction to that of rotor magnetic field. Due to this field, there is induced e.m.f. in the rotor winding. This causes overheating of the rotor.

Rotor earth fault protection and rotor temperature indicators are the essential and are provided to large rating generators.

4.2.3 Abnormal Running Conditions

In practice there are number of situations in which generator is subjected to some abnormal running conditions. The protection must be provided against the abnormal conditions. These abnormal conditions include,

1. Overloading
2. Overspeeding
3. Unbalanced loading
4. Overvoltage
5. Failure of prime mover
6. Loss of excitation (Field failure)
7. Cooling system failure.

4.2.3.1 Overloading

Due to the continuous overloading, the overheating of the stator results. This may increase the winding temperature. If this temperature rise exceeds certain limit, the insulation of the winding may get damaged. The degree of overloading decides the effects and temperature rise. The overcurrent protection is generally set to very high value hence continuous overloads of less value than the setting cannot be sensed by overcurrent protection.

4.2.3.2 Overspeeding

In case of hydraulic generators a sudden loss of load results in overspeeding of the generator. This is because the water flow to the turbine cannot be stopped or reduced instantly. Generally a turbogovernor is provided to prevent the overspeeding. But if there is any fault in the turbine governor then the dangerous overspeeding may take place. Hence it is necessary to supervise the working of turbine governor and take some corrective measures if there is some fault in the governor.

4.2.3.3 Unbalanced Loading

The unbalanced loading of the generator results in the circulation of negative sequence currents. These currents produce the rotating magnetic field. This rotating magnetic field rotates at the synchronous speed with respect to rotor. The direction of rotation of this magnetic field is opposite to that of rotor. Hence effectively the relative speed between the two is double the synchronous speed.

Thus the e.m.f. gets induced, having double the normal frequency, in the rotor winding. The circulating currents due to the induced e.m.f. are responsible to overheat the rotor winding as well as rotor stampings. Continuous unbalanced load more than 10 % of the rated load causes tremendous heating which is dominant in case of cylindrical rotor of turbo alternators.

The reasons for the unbalanced load conditions are,

1. Occurrence of unsymmetrical faults near the generating station.
2. The failure of circuit breaker near the generating station in clearing all the three phases.

Negative sequence protection is important to prevent dangerous situations due to negative sequence currents which are because of unbalanced load conditions.

4.2.3.4 Overvoltage

The overvoltages are basically due to the overspeeding of generators. Another reason for the overvoltages is the faulty operation of voltage regulators. Not only the internal overvoltages are dangerous but atmospheric surge voltages can also reach to the generators. Such atmospheric surge voltages are generated by direct lighting strokes to the aerial lines of high voltage system. Inductively and capacitively, these surges can get transferred to the generator. To protect the generators from surge voltages, the surge arresters and surge capacitors are often used.

At the time of restriking across the contacts of circuit breakers, the transient over voltages get generated. Such surges are called switching surges and can be limited by the uses of modern circuit breakers. R-C surge suppressors also help in reducing switching surges. Another situation, when the transient overvoltages are generated, is when the arcs are grounded. During arcing grounds, the transient voltages having amplitudes five times more than the normal line to neutral peak amplitude are generated. Such transient voltages are dangerous and can be reduced by using resistance earthing.

4.2.3.5 Failure of Prime Mover

The failure of prime mover results in motoring operation of synchronous generator. The generator draws active power from the network and continues to run at synchronous speed as a synchronous motor. This may lead to dangerous mechanical conditions if allowed to persist for more than twenty seconds. The serious overheating of the steam turbine blades may result. To prevent this the reverse power protection achieved by directional power relays is used.

4.2.3.6 Loss of Excitation

The loss of excitation or reduced excitation is possible due to the field failure i.e. opening of field winding or due to short circuit in field or due to some fault in exciter system.

Such loss of excitation results in loss of synchronism within a second and this causes the increase in speed of the generator. Since power input to the machine remains same, the generator starts working as an induction generator, drawing the reactive power from the bus. The machine starts drawing an exciting current from the system, which is equal to the full load rated value. This leads to the overheating of the stator winding and the rotor body due to induced currents. The loss of excitation may also lead to the pole slipping condition which results in the voltage reduction for the output above half the rated load.

Loss of excitation should not persist for long and corrective measures like disconnection of alternator should be taken immediately. For this a tripping scheme can be used which can trip the generator circuit breaker immediately when there is a field failure.

4.2.3.7 Cooling System Failure

The failure of cooling system also causes severe overheating to rise the temperature above safe limit. This may lead to insulation failure, causing some other faults to occur. The thermocouples or resistance thermometers are used in large machines to sense the temperature. The corrective measures are taken whenever the temperature exceeds the limit.

Apart from the above dominant abnormal conditions, some conditions may exist which are rare in practice. Such conditions are wrong synchronization, local overheating, leakage in hydrogen circuit, moisture in the generator winding, oxygen in pure water circuit, vibrations, bearing currents, excessive bearing temperature etc.

Review Questions

1. *What are the abnormal operating conditions and faults to which a modern turbo alternator is likely to be subjected ?* **AU : Dec.-06, May-07, Marks 6**
2. *Explain about the : Faults occur in generator.* **AU : Dec.-22, Marks 6**

4.3 Basic Differential Protection Scheme for Generators AU : Dec.-17

A basic differential protection scheme used for the generators is shown in the Fig. 4.3.1. It is known that the differential relay operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined value.

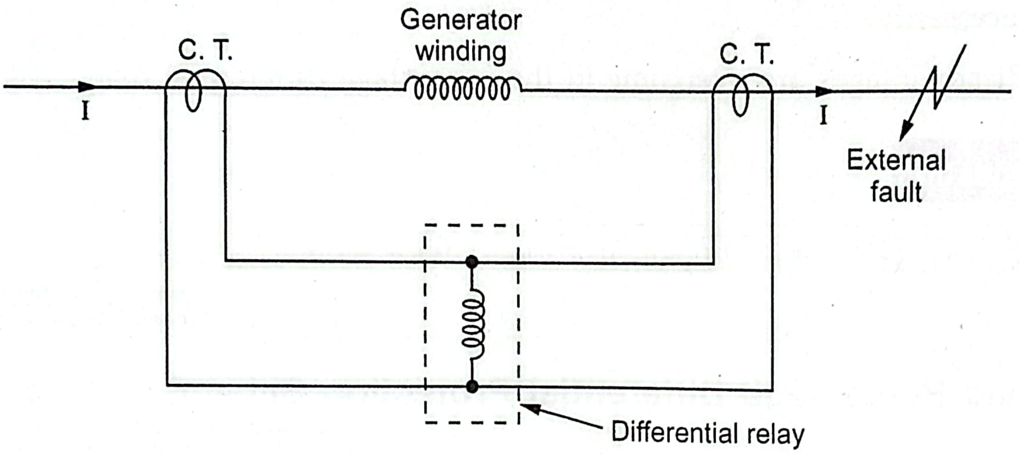


Fig. 4.3.1

Suppose the current I flows through the primary of C.T.s to the external fault. If the two C.T.s have same ratio, then no current will flow through the relay and it remains inoperative.

But now if an internal fault occurs at point X as shown in the Fig. 4.3.2, the current flows through the fault from both the sides. The primary currents are I_1 and I_2 while the secondary currents are i_1 and i_2. So the current flowing through the relay will be $i_1 + i_2$. Even some current flowing out of one side while a large current entering the other side will cause the differential current. Such a current is responsible to operate the relay.

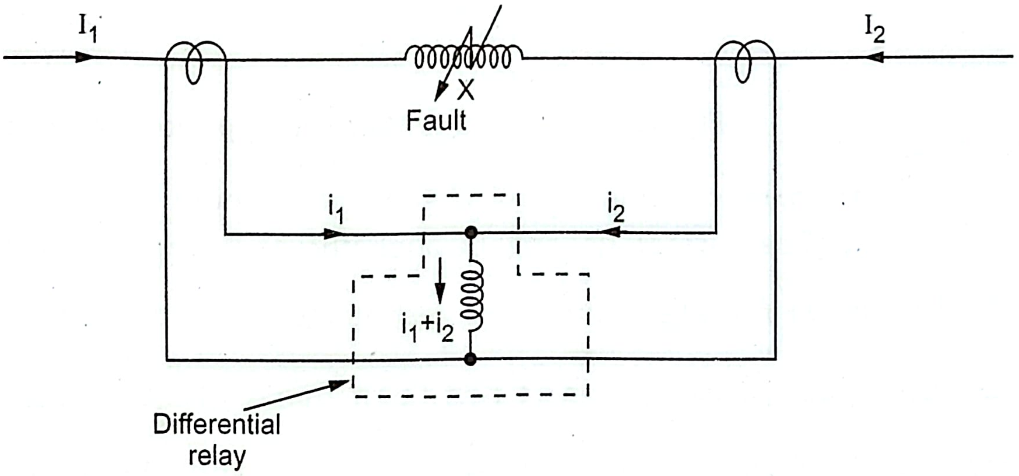


Fig. 4.3.2

Thus the relay current is proportional to the phasor difference between the currents entering and leaving the protected circuit and if the differential current exceeds the pickup value, the relay operates.

This basic differential scheme has following disadvantages :

1. This circuit operates inaccurately with heavy external faults.
2. The C.T.s may saturate and cause unequal secondary currents and the difference of secondary currents may approach the pickup value to operate the relay unnecessarily.

These disadvantages are overcome in the percentage differential relay.

Review Question

1. *Explain the basic differential protection scheme. What are its disadvantages ?*

AU : Dec.-17, Marks 8

4.4 Basic Percentage Differential Protection Scheme for Generators

AU : Dec.-10, 14, 17, May-22

This protection scheme is also called biased differential protection scheme. The Fig. 4.4.1 shows the connections of the percentage differential relay, in such a protection scheme.

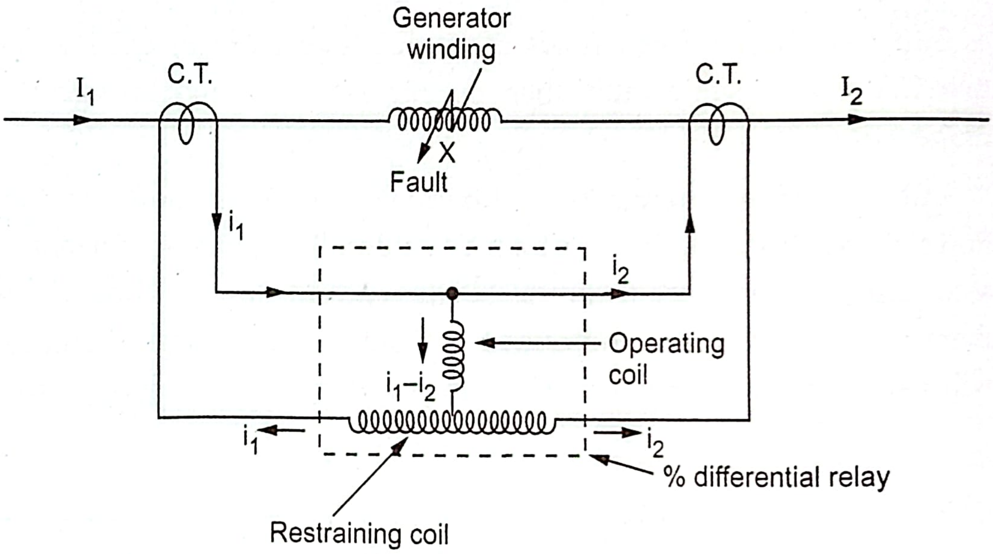


Fig. 4.4.1 Percentage differential protection scheme

The fault occurs at point X and the primary currents in the circuit are I_1 and I_2. The C.T. secondary currents are i_1 and i_2. The current flowing through the operating coil of the relay is $i_1 - i_2$. While the current flowing through the restraining coil of the relay is $\left(\frac{i_1+i_2}{2}\right)$. This is because the operating coil is connected to the midpoint of the restraining coil.

Thus if the number of turns of the restraining coil is N then i_1 flows through $\frac{N}{2}$ and i_2 flows through remaining $\frac{N}{2}$. The total ampere turns are $\frac{i_1 N}{2}+\frac{i_2 N}{2}$ i.e. $N\left(\frac{i_1+i_2}{2}\right)$.

This is as good as the flow of current $\left(\frac{i_1+i_2}{2}\right)$ through the entire restraining coil.

The operating characteristics of such a biased differential relay is shown in the Fig. 4.4.2. The characteristics shows that except at low currents, ratio of differential operating current to average restraining current is a fixed percentage. Hence the relay is called the percentage differential relay.

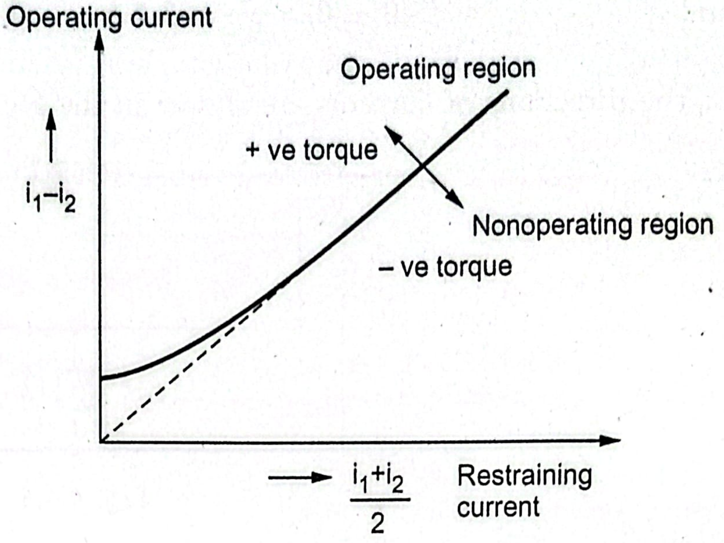


Fig. 4.4.2

This basic percentage differential protection scheme forms the basis of the practically very commonly used percentage differential protection scheme for alternator stator windings. This popular scheme is known as Biased differential protection or Merz-Price protection.

Example 4.4.1 *An alternator stator winding protected by a percentage differential relay is shown in the Fig. 4.4.3. The relay has 15 % slope of characteristics* $(I_1 - I_2)$ *against* $(I_1 + I_2 / 2)$*. The high resistance ground fault has occurred near the grounded neutral end of the generator winding while the generator is carrying load. The currents flowing at each end of the generator winding are also shown. Assuming C.T. ratio to be 500/5 A, will the relay operate to trip the circuit breaker ?*

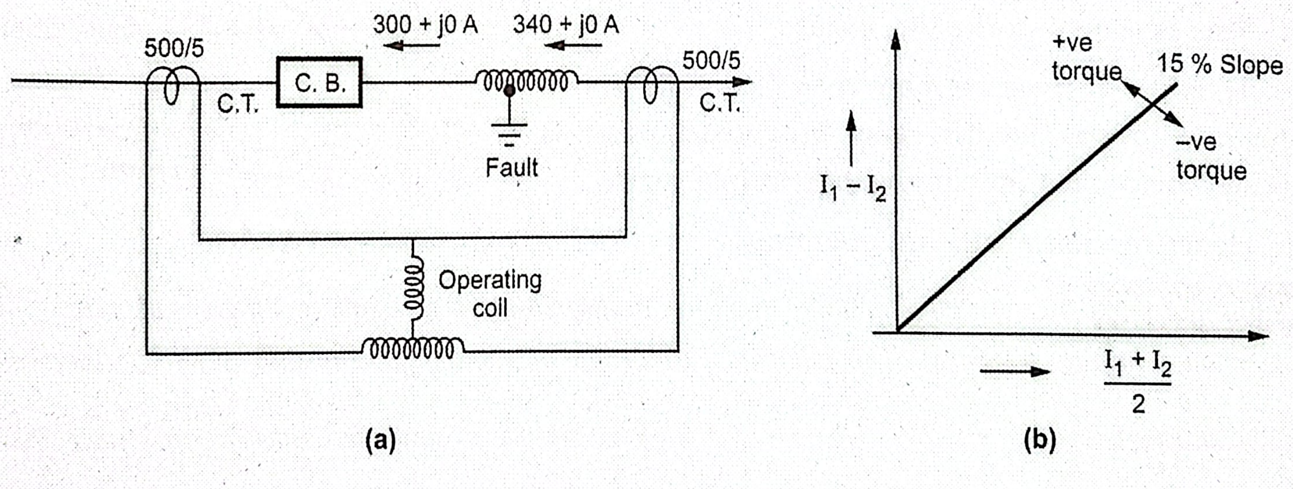


Fig. 4.4.3

Solution : From the given current at two ends, let us calculate C.T. secondary currents at two ends,

$$\therefore \quad i_1 = (300 + j0) \times \frac{5}{500} = 3 \text{ A}$$

and $$i_2 = (340 + j0) \times \frac{5}{500} = 3.4 \text{ A}$$

The directions of currents are shown in the Fig. 4.4.4.

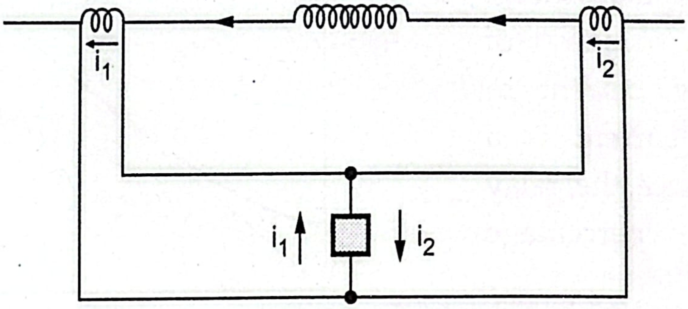


Fig. 4.4.4

The current flowing through the relay coil is $i_1 - i_2$.

$$\therefore \quad i_1 - i_2 = 3 - 3.4 = -0.4 \text{ A}$$

While $$\frac{i_1 + i_2}{2} = \frac{3 + 3.4}{2} = 3.2 \text{ A}$$

From the characteristics of 15 % slope, corresponding to $\frac{i_1 + i_2}{2}$ the out of balance current required is,

$$i_1 - i_2 = \text{Slope} \times \left(\frac{i_1 + i_2}{2}\right)$$

$$= 0.15 \times 3.2 = \mathbf{0.48 \text{ A}}$$

This is shown in the Fig. 4.4.5.

Thus $i_1 - i_2$ must be more than 0.48 A i.e. above the line to operate the relay but actual point is located below the line in negative torque region.

Hence the **relay will not operate.**

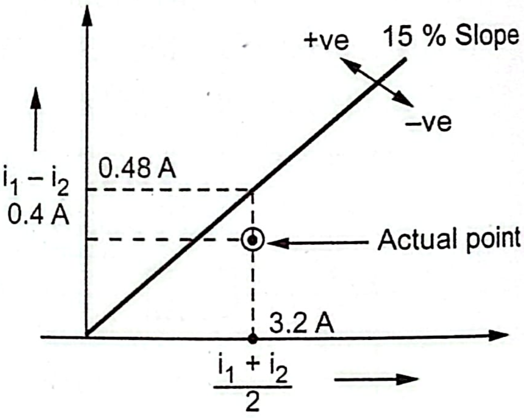


Fig. 4.4.5

Example 4.4.2 *An alternator stator winding protected by a percentage differential relay is shown in Fig. 4.4.6 (a). The relay has 0.15 amp minimum pick up and a 12 % slope of characteristics* $(i_1 - i_2)$ *V*$_s$ $\left(\frac{i_1 + i_2}{2}\right)$. *A high resistance ground fault has occured near the grounded neutral end of the generator winding while generator is carrying load. The currents flowing at each end of the generator winding are shown in Fig. 4.4.6. Assuming that the CT's have 400/5 amps ratio and no inaccuracies will the relay trip the generator CB under this fault condition.*

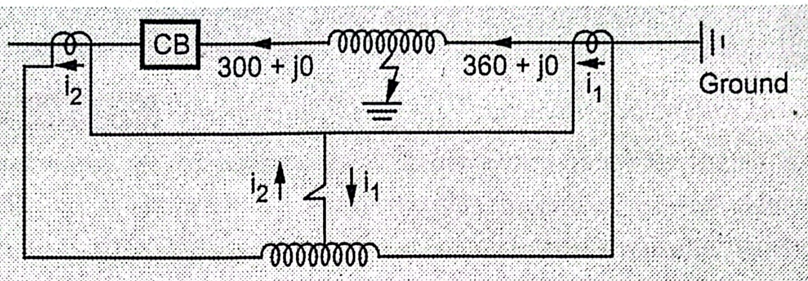


Fig. 4.4.6 (a)

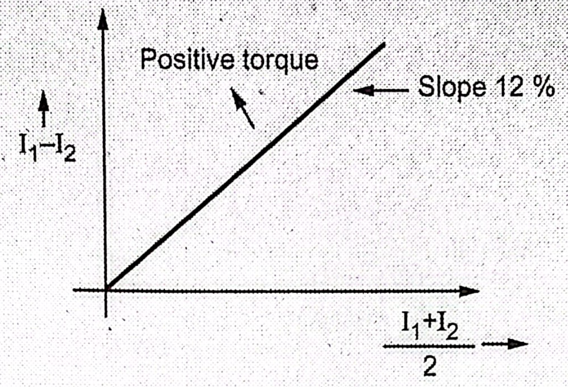


Fig. 4.4.6 (b)

Solution : From the given current at two ends, let us calculate C.T. secondary currents at two ends,

$$i_2 = (300+j0)\times\frac{5}{400} = 3.75 \text{ A} \quad \text{and} \quad i_1 = (300+j0)\times\frac{5}{400} = 4.5 \text{ A}$$

$$\text{The relay coil current} = i_1 - i_2 = 0.75 \text{ A}$$

$$\frac{i_1+i_2}{2} = 4.125 \text{ A}$$

From the characteristics of 12 % slope, corresponding to $\left(\frac{i_1+i_2}{2}\right)$, the out of balance current required is,

$$i_1 - i_2 = \text{slope} \times \left(\frac{i_1+i_2}{2}\right) = 0.12 \times 4.125 = 0.495 \text{ A}$$

Thus $i_1 - i_2$ must be more than 0.495 A for relay to operate. And actually it is 0.75 A. Hence **the relay will operate :**

Actual point is located in positive torque region. Slope of line through actual point is

$$= \frac{(i_1-i_2)}{\left(\frac{i_1+i_2}{2}\right)} = \frac{0.95}{4.125}\times 100 = \mathbf{18.18\ \%}$$

As this slope is more than 12 % of the characteristics given, **relay will operate.**

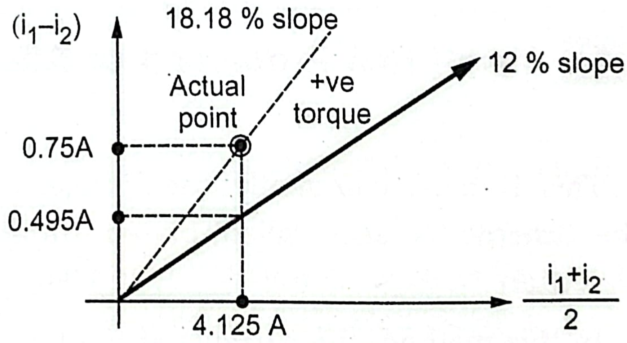


Fig. 4.4.7

Review Questions

1. *Explain the biased differential protection scheme for alternators.* **AU : Dec.-10, 17, Marks 8**
2. *The Fig. 4.4.8 shows percentage differential relay applied to the protection of an alternator winding. The relay has 10 % slope of characteristics* $I_1 - I_2$ *vs* $(I_1 + I_2) / 2$.
   A high resistance ground fault occurred near the grounded neutral end of the generator winding while generator is carrying load. As a consequence, the currents in amperes flowing at each end of the winding are shown in Fig. 4.4.8 (b). Assuming C.T. ratio of 400/5 amperes, will the relay operate to trip the breaker. **[Ans. : Relay will not operate]**

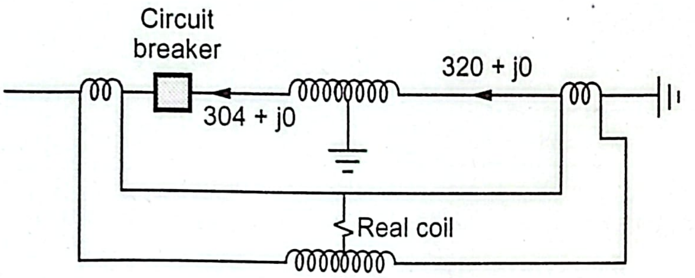


Fig. 4.4.8 (a)

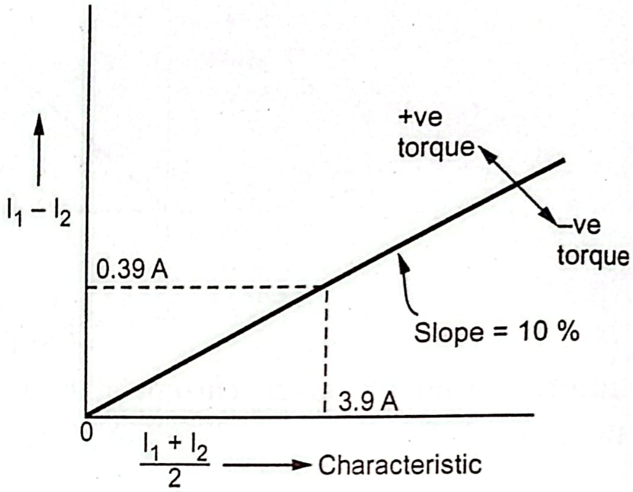


Fig. 4.4.8 (b)

3. *The Fig. 4.4.9 shows the percentage differential relay used for the protection of an alternator winding. The relay has minimum pickup current of 0.25 A and has a % slope of 10 %. A high resistance ground fault occurs near the grounded neutral end of the generator winding with the current distribution as shown in the Fig. 4.4.9. Assume a C.T. ratio of 400 : 5, determine if relay will operate.*

   [Ans. : Relay will not operate]

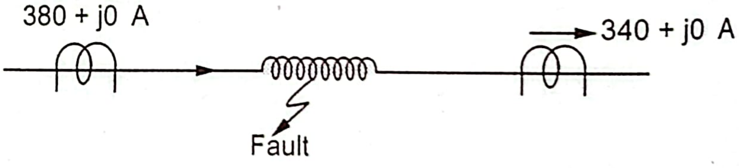


Fig. 4.4.9

4. *Describe with a neat sketch, the percentage differential protection of a modern alternator.* **AU : Dec.-14, May-22, Marks 10**

4.5 Merz-Price Protection of Alternator Stator Windings

AU : May-06,13,14,22, Dec.-06,08,10,22

This is most commonly used protection scheme for the alternator stator windings. The scheme is also called biased differential protection and percentage differential protection.

In this method, the currents at the two ends of the protected section are sensed using current transformers. The wires connecting relay coils to the current transformer secondaries are called pilot wires.

Under normal conditions, when there is no fault in the windings, the currents in the pilot wires fed from C.T. secondaries are equal. The differential current $i_1 - i_2$ through the operating coils of the relay is zero. Hence the relay is inoperative and system is said to be balanced.

When fault occurs inside the protected section of the stator windings, the differential current $i_1 - i_2$ flows through the operating coils of the relay. Due to this current, the relay operates. This trips the generator circuit breaker to isolate the faulty section. The field is also disconnected and is discharged through a suitable impedance.

The Fig. 4.5.1 shows a schematic arrangement of Merz-Price protection scheme for a star connected alternator.

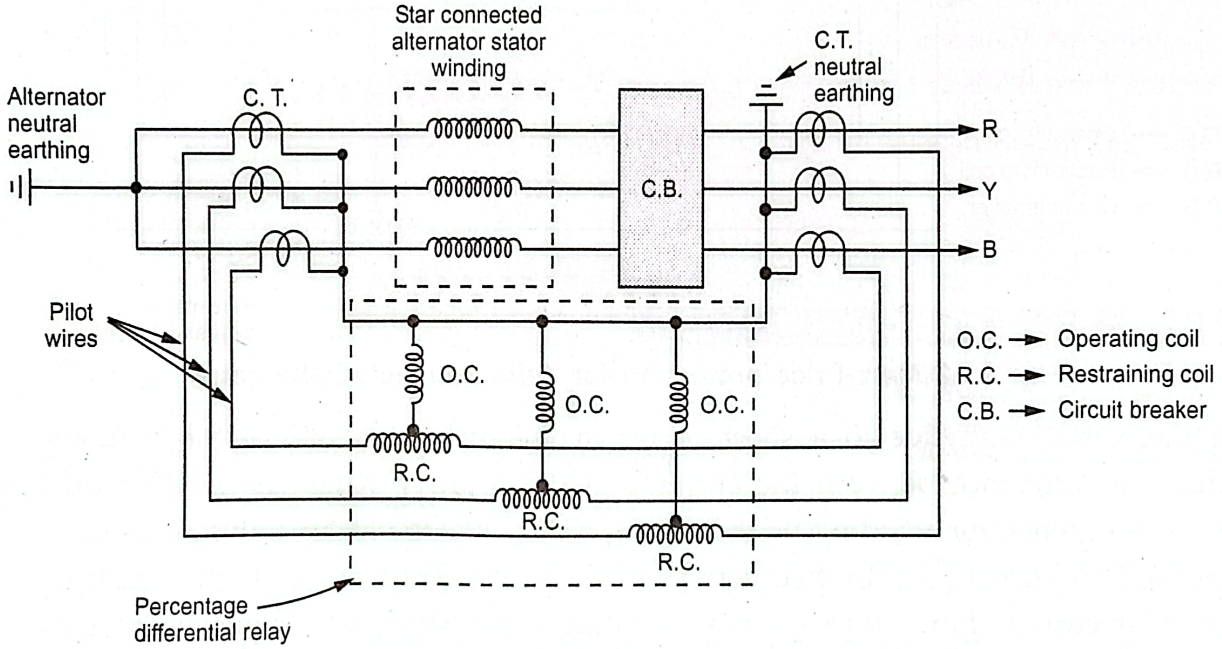

Star connected alternator stator winding
Alternator neutral earthing
C. T.
C.T. neutral earthing
C.B.
R
Y
B
Pilot wires
O.C.
O.C.
O.C.
R.C.
R.C.
R.C.
O.C. → Operating coil
R.C. → Restraining coil
C.B. → Circuit breaker
Percentage differential relay

Fig. 4.5.1 Merz-Price protection for star connected alternator

The differential relay gives protection against short circuit fault in the stator winding of a generator. The C.T.s are connected in star and are provided on both, the outgoing side and machine winding connections to earth side. The restraining coils are energized from the secondary connection of C.T.s in each phase, through pilot wires. The operating coils are energized by the tappings from restraining coils and the C.T. neutral earthing connection.

The similar arrangement is used for the delta connected alternator stator winding, as shown in the Fig. 4.5.2. (See Fig. 4.5.2 on next page)

The C.T.s on the delta connected machine winding side are connected in delta while the C.T.s at outgoing ends are connected in star. The restraining coils are placed in each phase, energized by the secondary connections of C.T.s while the operating coils are energized from the restraining coil tappings and the C.T. neutral earthing.

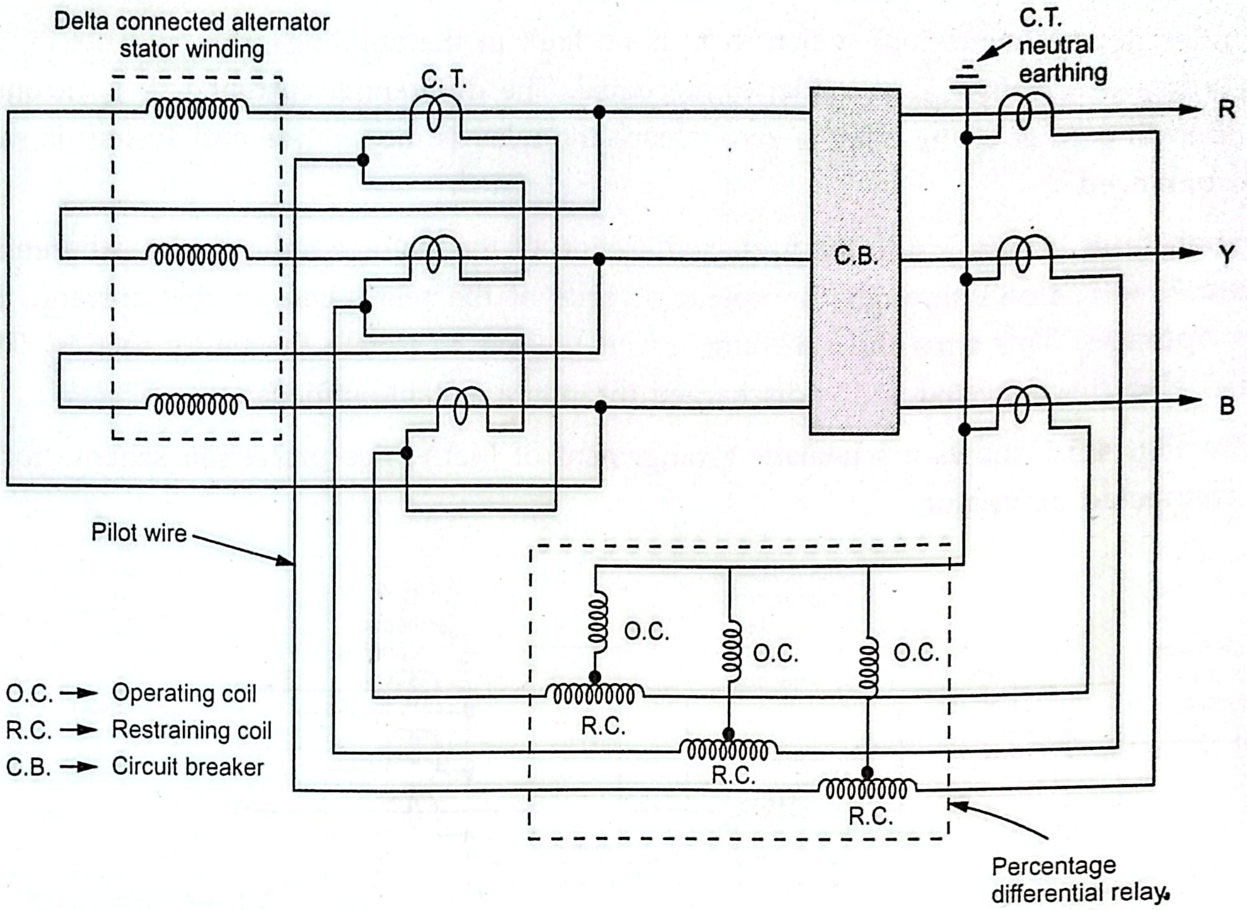

Delta connected alternator stator winding
C. T.
C.T. neutral earthing
C.B.
R
Y
B
Pilot wire
O.C.
O.C.
O.C.
R.C.
R.C.
R.C.
O.C. → Operating coil
R.C. → Restraining coil
C.B. → Circuit breaker
Percentage differential relay

Fig. 4.5.2 Merz-Price protection for delta connected alternator

If there is a fault due to a short circuit in the protected zone of the windings, it produces a difference between the currents in the primary windings of C.T.s on both sides of the generator winding of the same phase. This results in a difference between the secondary currents of the two current transformers. Thus, under fault conditions, a differential current flows through the operating coils which is responsible to trip the relay and open the circuit breaker. The differential relay operation depends on the relation between the current in the operating coil and that in the restraining coil.

In addition to the tripping of circuit breaker, the percentage differential relay trip a hand reset multicontact auxiliary relay. This auxiliary relay simultaneously initiates the following operations,

1. Tripping of the main circuit breaker of generator.
2. Tripping of the field circuit breaker.
3. Tripping of the neutral circuit breaker if it is present.
4. Shut down of the prime mover.
5. Turn on of CO_2 gas if provided for safety of generator under faulty conditions.
6. Operation of alarm and/or annunciator to indicate the occurrence of the fault and the operation of the relay the field must be opened immediately otherwise it starts feeding the fault.

When differential relaying is used for the protection, C.T.s at both the ends of generator must be of equal ratio and equal accuracy otherwise if the error is excessive, wrong operation of the relay may result. The causes of unequal currents on both the sides of C.T.s without any fault are ratio errors, unequal lengths of the leads, unequal secondary burdens etc.

This scheme provides very fast protection to the stator winding against phase to phase faults and phase to ground faults. If the neutral is not grounded or grounded through resistance then additional sensitive earth fault relay should be provided.

The **advantages** of this scheme are,

1. Very high speed operation with operating time of about 15 msec.
2. It allows low fault setting which ensures maximum protection of machine windings.
3. It ensures complete stability under the most severe through and external faults.
4. It does not require current transformers with air gaps or special balancing features.

Review Questions

1. *Explain with neat diagram the application of Merz-Price circulating current principle for protection of alternator.* **AU : May-06, 13, Dec.-06, 08, 10, Marks 12**
2. *Write a note on generator protection.* **AU : May-14,22, Marks 8**
3. *Explain the : Merz-price protection of a generator.* **AU : Dec.-22, Marks 7**

4.6 Restricted Earth Fault Protection of Generator

AU : Dec.-04,05,06,08,16,18, April-05, May-06,07,11,12,18

Generally Merz-Price protection based on circulating current principle provides the protection against internal earth faults. But for large generators, as these are costly, an additional protection scheme called restricted earth fault protection is provided.

When the neutral is solidly grounded then the generator gets completely protected against earth faults. But when neutral is grounded through earth resistance, then the stator windings get partly protected against earth faults. The percentage of winding protected depends on the value of earthing resistance and the relay setting.

In this scheme, the value of earth resistance, relay setting, current rating of earth resistance must be carefully selected. The earth faults are rare near the neutral point as the voltage of neutral point with respect to earth is very less. But when earth fault occurs near the neutral point then the insufficient voltage across the fault drives very low fault current than the pick up current of relay coil. Hence the relay coil remains inoperative. Thus 15 to 20 % winding from the neutral side remains unprotected in this scheme. Hence it is called restricted earth fault protection. It is usual practice to protect 85 % of the winding.

The restricted earth fault protection scheme is shown in the Fig. 4.6.1.

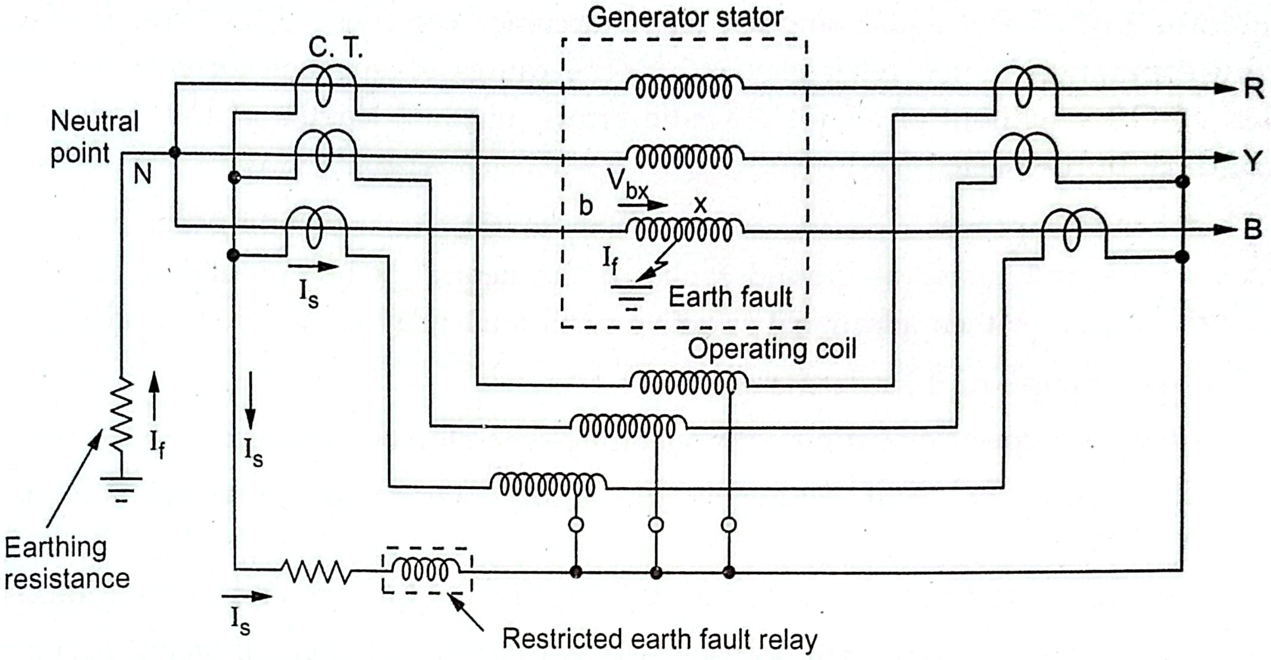


Fig. 4.6.1 Restricted earth fault protection

Consider that earth fault occurs on phase B due to breakdown of its insulation to earth, as shown in the Fig. 4.6.1. The fault current I_f will flow through the core, frame of machine to earth and complete the path through the earthing resistance. The C.T. secondary current I_s flows through the operating coil and the restricted earth fault relay coil of the differential protection. The setting of restricted earth fault relay and setting of overcurrent relay are independent of each other. Under this secondary current I_s, the relay operates to trip the circuit breaker. The voltage V_{bx} is sufficient to drive the enough fault current I_f when the fault point x is away from the neutral point.

If the fault point x is nearer to the neutral point then the voltage V_{bx} is small and not sufficient to drive enough fault current I_f. And for this I_f, relay cannot operate. Thus part of the winding from the neutral point remains unprotected. To overcome this, if relay setting is chosen very low to make it sensitive to low fault currents, then wrong operation of relay may result. The relay can operate under the conditions of heavy through faults, inaccurate C.T.s, saturation of C.T.s etc. Hence practically 15 % of winding from the neutral point is kept unprotected, protecting the remaining 85 % of the winding against phase to earth faults.

4.6.1 Effect of Earth Resistance on % of Winding Unprotected

Let us see the effect of earth resistance on the % of the winding which remains unprotected.

Consider the earth resistance R used to limit earth fault current as shown in the Fig. 4.6.2.

The value of the resistance R limits the earth fault current.

If the resistance R is very small i.e. the neutral is almost solidly grounded, then the fault current is very high. But high fault currents are not desirable hence small R is not preferred for the large machines.

For low resistance R, the value of R is selected such that full load current passes through the neutral, for a full line to neutral voltage V.

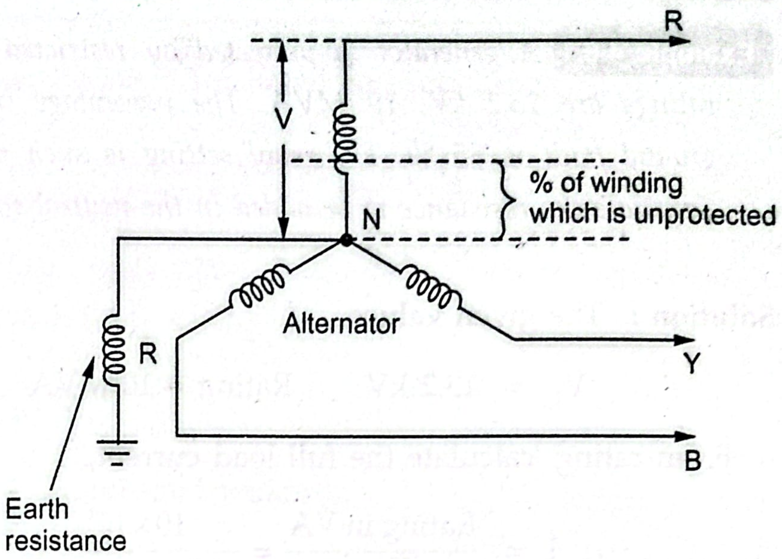


Fig. 4.6.2

In medium resistance R, the earth fault current is limited to about 200 A for full line to neutral voltage V, for a 60 MW machine.

In high resistance R, the earth fault current is limited to about 10 A. This is used for distribution transformers and generator-transformer units.

Now higher the value of earth resistance R, less is the earth fault current and less percentage of winding gets protected. Large percentage of winding remains unprotected.

Let V = Full line to neutral voltage

I = Full load current of largest capacity generator

R = Earth resistance

Then the value of the resistance R is,

$$R = \frac{V}{I}$$

And the percentage of winding unprotected is given by,

$$\boxed{\% \text{ of winding } \textbf{unprotected} = \frac{RI_0}{V} \times 100}$$

where I_0 = Minimum operating current in the primary of C.T.

If relay setting used is 15 % then I_0 is 15 % of the full load current of the **largest machine** and so on.

Greater percentage of windings of small capacity machines running parallel get protected.

Example 4.6.1 *A generator is protected by restricted earth fault protection. The generator ratings are 13.2 kV, 10 MVA. The percentage of winding protected against phase to ground fault is 85 %. The relay setting is such that it trips for 20 % out of balance. Calculate the resistance to be added in the neutral to ground connection.*

AU : Dec.-08,16, Marks 8

Solution : The given values,

$$V_L = 13.2 \text{ kV} \qquad \text{Rating} = 10 \text{ MVA}$$

From rating, calculate the full load current,

$$I = \frac{\text{Rating in VA}}{\sqrt{3}\, V_L} = \frac{10 \times 10^6}{\sqrt{3} \times 13.2 \times 10^3} = 437.386 \text{ A}$$

Relay setting is 20 % out of balance i.e. 20 % of the rated current activates the relay.

$$\therefore \quad I_o = 4387.386 \times \frac{20}{100} = 87.477 \text{ A} = \text{Minimum operating current}$$

$$V = \text{Line to neutral voltage} = \frac{V_L}{\sqrt{3}} = \frac{13.2 \times 10^3}{\sqrt{3}} = 7621.02 \text{ V}$$

% of winding unprotected = 15 % as 85 % is protected

$$\therefore \quad 15 = \frac{RI_o}{V} \times 100 \qquad \text{i.e.} \qquad 15 = \frac{R \times 87.477}{7621.02} \times 100$$

$$\therefore \quad R = \mathbf{13.068\ \Omega}$$

Example 4.6.2 *A star connected, 3 phase, 10 MVA, 6.6 kV alternator has a per phase reactance of 10 %. It is protected by Merz-price circulating-current principle which is set to operate for fault currents not less than 175 A. Calculate the value of earthing resistance to be provided in order to ensure that only 10 % of the alternator winding remains unprotected.*

AU : May-12,18, Marks 6

Solution : The given values are,

$$V_L = 6.6 \text{ kV} \qquad \text{Rating} = 10 \text{ MVA}$$

$$\text{Rating} = \sqrt{3}\, V_L\, I_L \qquad \text{i.e.} \quad 10 \times 10^6 = \sqrt{3} \times 6.6 \times 10^3 \times I_L$$

$$I_L = \frac{10 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3} = 874.77 \text{ A} = I = \text{Rated current}$$

$$V = \frac{V_L}{\sqrt{3}} = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810.51 \text{ V}$$

$$\% \text{ Reactance} = \frac{IX}{V} \times 100$$

where X = Reactance per phase and I = Rated current

$$\therefore \quad 10 = \frac{874.77\ X}{3810.51} \times 100 \qquad \text{i.e.} \quad X = 0.435\ \Omega$$

$\therefore$ Reactance of unprotected winding

$$= (\%\text{ of unprotected winding}) \times (X)$$

$$= \frac{10}{100} \times 0.435 = 0.0435\ \Omega$$

$$v = \text{Voltage induced in unprotected winding}$$

$$= \frac{10}{100} \times V = 0.1 \times 3810.51 = 381.051$$

$$i = \text{Fault current} = 175\ \text{A}$$

$$Z = \text{Impedance offered to the fault}$$

$$= \frac{v}{i} = \frac{381.051}{175} = 2.178\ \Omega \qquad \ldots (1)$$

Now $Z = r + j$ (reactance of unprotected winding)

$$Z = r + j(0.0435)\ \Omega$$

$$\therefore \quad |Z| = \sqrt{r^2 + (0.0435)^2} \qquad \ldots (2)$$

Equating equations (1) and (2),

$$2.178 = \sqrt{r^2 + (0.0435)^2}$$

$$\therefore \quad 4.743 = r^2 + 1.89225 \times 10^{-3}$$

$$\therefore \quad r = \mathbf{2.177\ \Omega}$$

This is the earthing resistance required.

Example 4.6.3 *A 13.2 kV, 3 phase, 100 MW at 0.8 p.f. lag, alternator has reactance of 0.2 p.u. If it is equipped with a circulating current differential protection set to operate atleast at 500 A fault current, determine the magnitude of the neutral grounding resistance that leaves the 10 % of the winding unprotected.*

Solution : The given values are,

$$V_L = 13.2\ \text{kV} \quad \cos\phi = 0.8 \quad P = 100\ \text{MW} \quad X = 0.2\ \text{p.u.}$$

Now $P = \sqrt{3}\, V_L I_L \cos\phi$ i.e. $100 \times 10^6 = \sqrt{3} \times 13.2 \times 10^3 \times I_L \times 0.8$

$$\therefore \quad I_L = 5467.33\ \text{A} = I = \text{Full load current}$$

The p.u. reactance is given by,

$$\text{p.u. } X = \frac{I X}{V} \quad \text{where } X = \text{Reactance per phase}$$

$$\therefore \quad 0.2 = \frac{5467.33 X}{\left(\frac{13.2\times10^3}{\sqrt{3}}\right)} \quad \text{where } V = \frac{V_L}{\sqrt{3}}$$

$$\therefore \quad X = 0.2787\ \Omega \text{ per phase}$$

% of unprotected winding = 10 %

$$\therefore \quad \text{Reactance of unprotected winding} = \frac{10}{100}\times0.2787 = 0.02787\ \Omega$$

Voltage induced in 10 % of unprotected winding

$$= \frac{10}{100}\times V = \frac{10}{100}\times\frac{13.2\times10^3}{\sqrt{3}} = 762.1023\ V$$

Let this voltage be $v = 762.1023\ V$

$$Z = \sqrt{r^2+x^2} \quad \text{where} \quad Z = \text{Impedance offered to the fault}$$

and r = Resistance in neutral and x = Reactance of 10 % of winding

Now $Z = \frac{v}{i}$

where v = Voltage induced in 10 % winding = 762.1023 V

i = Fault current = 500 A

$$\therefore \quad \sqrt{r^2+x^2} = \frac{762.1023}{500} \quad \text{i.e.} \quad \sqrt{r^2+(0.02787)^2} = 1.5242$$

$$\therefore \quad r^2+(0.02787)^2 = 2.3232 \quad \text{i.e.} \quad r^2 = 2.3224$$

$$\therefore \quad r = \mathbf{1.524\ \Omega}$$

This is the required resistance in neutral earthing.

Example 4.6.4 *A 6.6 kV, star connected alternator has a transient reactance of 2 Ω per phase and negligible winding resistance. It is protected by circulating current Merz-Price protection. The alternator neutral is earthed through the resistance of 7.5 Ω. The relays are set to operate when there is out of balance current of 1 A in secondary of 500/5 A current transformers. How much % of winding is protected against earth fault ?*

AU : Dec.-22, Marks 15

Solution : The given values,

$$V_L = 6.6\ kV \qquad X = 2\ \Omega/\text{phase} \qquad r = 7.5\ \Omega \qquad \text{C.T.} = 500/5$$

Let the x % of winding is unprotected.

Reactance of unprotected winding = $\frac{x}{100} \times 2 = 0.02 \text{ x } \Omega$

$$V = \frac{V_L}{\sqrt{3}} = \frac{6.6 \times 10^3}{\sqrt{3}} = 3810.511 \text{ V} \qquad \text{... Full voltage}$$

$$V = \text{Voltage across unprotected winding}$$

$$= \frac{x}{100} \times 3810.511 = 38.10511 \text{ x V}$$

$$r = 7.5 \ \Omega$$

Z = Impedance offered to the fault = r + j(0.02 x) = 7.5 + j(0.02 x) Ω

$$\therefore \quad |Z| = \sqrt{(7.5)^2 + (0.02 \text{ x})^2}$$

i = Fault current = Out of balance secondary current × C.T. ratio

$$= 1 \times \frac{500}{5} = 100 \text{ A}$$

$$\therefore \quad |Z| = \frac{V}{i} \qquad \text{i.e.} \quad \sqrt{(7.5)^2 + (0.02 \text{ x})^2} = \frac{38.10511 x}{100}$$

$$\therefore \quad (7.5)^2 + (0.02 \text{ x})^2 = 0.1452 \text{ x}^2 \quad \text{i.e.} \quad 56.25 + 4 \times 10^{-4} x^2 = 0.1452 \text{ x}^2$$

$$\therefore \quad 0.1448 \text{ x}^2 = 56.25 \qquad \text{i.e.} \quad x^2 = 388.4668$$

$$\therefore \quad x = 19.7 \ \% \qquad \text{... \% of winding unprotected.}$$

$$\therefore \quad \text{\% of winding protected} = 100 - 19.7 = \mathbf{80.29 \ \%}$$

Example 4.6.5 *An alternator rated 10 kV protected by balanced circulating current system has its neutral grounded through a resistance of 10 ohms. The protective relay is set to operate when there is an out of balance current of 1.8 amperes in the pilot wires which are connected to the secondary of current transformers with ratio 1000/5.*

Determine :

i) The percentage winding which remains unprotected.

ii) The minimum value of the earthing resistance required to protect 80 % of the winding.

AU : May-11, Dec.-18, Marks 16

Solution : V_L = 10 kV, R = 10 Ω, C.T. ratio = 1000/5, i_o = 1.8 A

$$I_o = \text{Minimum operating line current (C.T. primary)}$$

$$= i_o \times \frac{1000}{5} = 1.8 \times \frac{1000}{5} = 360 \text{ A}$$

$$V = \text{Line to neutral voltage} = \frac{V_L}{\sqrt{3}} = \frac{10 \times 10^3}{\sqrt{3}} = 5773.5026 \text{ V}$$

i) % Winding unprotected $= \frac{RI_o}{V} \times 100 = \frac{10 \times 360}{5773.5026} \times 100 =$ **62.3538 %**

ii) It is necessary to give 80 % protection.

∴ % Winding unprotected = 100 − 80 = 20 %

$$\therefore \quad 20 = \frac{R \times 360}{5773.5026} \times 100$$

∴ R = **3.2075 Ω** ... Minimum earthing resistance required

Example 4.6.6 *A 3 phase, 10 MVA, 6.6 kV alternator supplies a load of 8 MVA at 0.8 p.f. and is being protected through Merz-price circulating current system and its relays are so set that they do not operate until the out of balance current occurs at 20 % of full load current. Calculate the value of earth resistance to be provided in order to ensure that only 10 % of alternator winding remains unprotected. Assume alternator reactance of 10 %. Neglect resistance of the alternator.* **AU : Dec.-04, Marks 8**

Solution : $V_L = 6.6$ kV, Rating = 10 MVA, $V = V_L/\sqrt{3} = 3810.5117$ V.

$$\therefore \quad \text{Rating} = \sqrt{3}\, V_L I_L$$

$$\therefore \quad I_L = \frac{10 \times 10^8}{\sqrt{3} \times 6.6 \times 10^3} = 874.7731 \text{ A}$$ ...Full load current

$$\therefore \quad \% \text{ Reactance} = \frac{IX}{V} \times 100$$ ...X = Reactance per phase

$$\therefore \quad 10 = \frac{874.7731X}{3810.5117} \times 100 \quad \text{i.e.} \quad X = 0.4356\ \Omega$$

Reactance of unprotected winding $= \frac{10}{100} \times 0.4356 = 0.04356\ \Omega$

v = Voltage induced in unprotected winding $= \frac{10}{100} \times V = 381.05117$ V

i = Fault current = 20 % of I_L = 174.954 A

∴ $Z = \frac{v}{i}$ = Impedance offered to fault = 2.178 Ω

But $Z = R + j\,0.04356\ \Omega$ i.e. $|Z| = \sqrt{R^2 + (0.04356)^2}$

∴ $(2.178)^2 = R^2 + (0.04356)^2$ i.e. R = **2.177 Ω** ...Earth resistance required

Example 4.6.7 *Current transformers of current ratio of 1000/5 A are used for protection of a star connected 3 phase, 10 MVA, 6.6 kV alternator. If the relay is set to operates for a minimum current of 0.5 A. Calculate the percentage of each phase stator winding which is unprotected against earth fault when the machine operates at normal voltage. Assume that star point of alternator is earthed through a resistance of 7.5 Ω.*

AU : April-05, May-07, Marks 8

Solution : Refer Example 4.6.1 for the procedure and verify the answer as **19.682 %.**

Example 4.6.8 *A 500 kVA, 6.6 kV star connected alternator has a synchronous reactance of 1.0 Ω per phase and negligible resistance. The differential relay operates if the out of balance current through it exceeds 30 % of the normal full load current of the alternator. The star point of the alternator is earthed through a resistance of 5 Ω . What percent of the stator winding is left unprotected ? Show that the effect of the alternator reactance can be neglected.*

AU : Dec.-05, Marks 12

Solution : The full load current,

$$I_L = \frac{V_A}{\sqrt{3}\ V_L} = \frac{500\times10^3}{\sqrt{3}\times6.6\times10^3} = 43.738\ \text{A}$$

$$\text{Out of balance current} = 30\ \%\ I_L = 0.3\times43.738 = 13.1214\ \text{A}$$

$$\text{Let winding unprotected} = x\ \%$$

$$\text{Impedance of x \% winding} = \frac{x}{100}(0+j1)$$

Value of earthing resistance = 5 Ω

∴ Total impedance at fault of the fault circuit = $[5 + j\ 0.01\ x]$

$$\text{Voltage induced in x \% of winding} = \frac{6.6\times10^3}{\sqrt{3}}\times\frac{x}{100} = \frac{66x}{\sqrt{3}}$$

$$\therefore\ \text{Out of balance current} = \frac{\text{Voltage induced}}{\text{Impedance}} \quad \text{i.e. } 13.1214 = \frac{\frac{66x}{\sqrt{3}}}{5+j\,0.01x} \qquad \ldots(1)$$

This is to be solved by trial and error method. Hence effect of alternator reactance can be neglected.

$$\therefore \quad 13.1214 = \frac{66x}{5\sqrt{3}} \quad \text{i.e.} \quad x = \mathbf{1.7217\ \%} \qquad \ldots\text{Winding unprotected}$$

The equation (1) can be solved as,

$$13.1214 = \frac{\frac{66x}{5\sqrt{3}}}{\sqrt{(5)^2+(0.01x)^2}} \qquad \text{... Considering magnitude}$$

$$\therefore \sqrt{25+(0.01x)^2} = 2.904\,x \quad \text{i.e.} \quad 25+(0.01x)^2 = 8.4334\,x^2$$

$$\therefore \qquad x = \mathbf{1.7217\ \%}$$

This shows that the reactance can be neglected without any error.

Example 4.6.9 *A three phase 20 MVA, 11 kV star connected alternator has a synchronous reactance of 2.5 Ω/phase and resistance of 0.75 Ω/phase. It is being protected by a Merz-Price balanced current system. Determine what portion of the winding remains unprotected and if the neutral of the alternator is earthed through a resistor of 5 Ω. Assume that the relay operates when the out of balance current exceeds 25 % of the load current.* **AU : May-06, Marks 12**

Solution : Let x % of winding being unprotected as shown in the Fig. 4.6.3.

$$V_L = 11\text{ kV}, \; R = 0.75\ \Omega/\text{ph}$$

$$X = 2.5\ \Omega/\text{ph}, \; R_e = 5\ \Omega$$

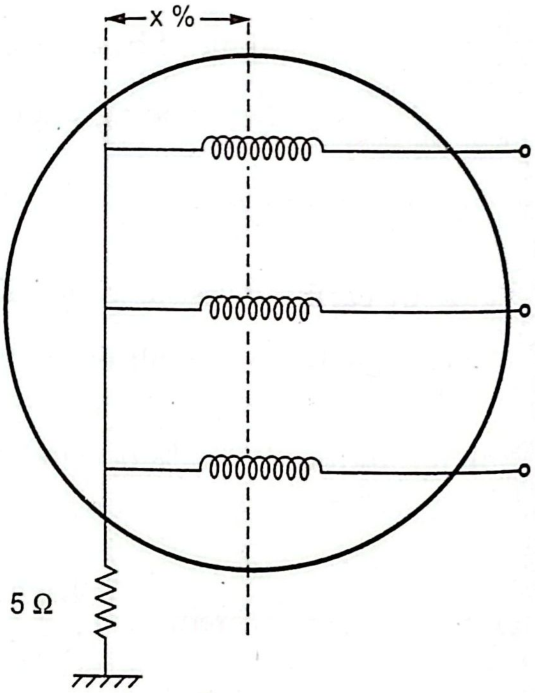


Fig. 4.6.3

The equivalent impedance offered by unprotected winding is

$$= \frac{x}{100}[0.75+j2.5]$$

The impedance offered to the fault current,

$$Z = 5+\frac{x}{100}[0.75+j2.5]$$

$$= \left(5+\frac{0.75x}{100}\right)+j\frac{2.5x}{100}$$

The full load current of the alternator

$$I_L = \frac{V_A}{\sqrt{3}\,V_L} = \frac{20\times10^6}{\sqrt{3}\times11\times10^3} = 1049.7277\text{ A}$$

Out of balance current which activates relay is,

$$i = 25\ \%\text{ of } I_L = \mathbf{262.4319\ A}$$

The voltage across unprotected winding is,

$$V_x = \frac{x}{100} \times V_P = \frac{x}{100} \times \frac{V_L}{\sqrt{3}} = 63.508\ x$$

and $$V_x = i\,|Z|$$

$$\therefore \quad 63.508\ x = 262.4319 \times \sqrt{\left(5+\frac{0.75x}{100}\right)^2 + \left(\frac{2.5x}{100}\right)^2}$$

$\therefore$ Solving, $x = \mathbf{21.44}$ ... Neglecting negative value

Thus **21.44** % winding remains unprotected.

Example 4.6.10 *A 5,000 kVA, 6,600 V star-connected alternator has a synchronous reactance of 2 ohm per phase and 0.5 ohm resistance. It is protected by a Merz-Price balanced current system which operates when the out of balance current exceeds 30 % of the load current. Determine what proportion of the alternator winding is unprotected if the star-point is earthed through a resistor of 6.5 ohms ?* **AU : Dec.-06, Marks 8**

Solution : Refer Example 4.6.8 for the procedure and verify the answer as **22.83 %.**

Review Questions

1. *Explain the restricted earth fault protection of alternators.* **AU : Dec.-05, Marks 8**
2. *A 3 phase, 2 pole, 11 kV, 10,000 kVA alternator has neutral earthed through a resistance of 7 ohms. The machine has current balance protection which operates upon out of balance current exceed 20 % of full load. Determine % of winding protected against earth fault.*

   (Ans. : 88.4 %)
3. *A 11 kV, 3 phase alternator has full load rated current of 200 A. Reactance of armature winding is 15 percent. The differential protection system is set to operate on earth fault currents of more than 200 A. Find the neutral earthing resistance, which gives earth fault protection to 90 % of stator winding.* **(Ans. : 3.145 Ω)**
4. *The neutral point of a 10,000 V alternator is earthed through a resistance of 10 ohms, the relay is set to operate when there is an out of balance current of 1 A. The C.T.s have a ratio of 1000/5. What percentage of the winding is protected against fault to earth and what must be minimum value of earthing resistance to give 90 % protection to each phase winding ?* **(Ans. : 62.5 %, 2.88 Ω)**
5. *A 50 MVA, 3-phase, 33 kV alternator is being protected by the use of circulating current balance scheme using 2000/5 ampere current transformer. The neutral of the generator is earthed through a NGR of 7.5 ohms. If the pick up current for the relay is just above 0.5 ampere, determine what percentage of the winding of each phase unprotected against earth when the machine operates at nominal voltage.* **(Ans. : 7.88 %)**

76. *A 50 MVA, 3 phase, 33 kV synchronous generator is protected by the Merz-Price protection using 1000/5 ratio C.T.s. It is provided with restricted earth fault protection with the earthing resistance of 7.5 Ω. Calculate the percentage of winding unprotected in each phase against earth faults if the minimum operating current of the relay is 0.5 A.* **(Ans. : 3.936 %)**

7. *The neutral point of a 10,000 V alternator is earthed through a resistance of 10 Ω, the relay is said to operate when there is an out of balance current of 1 A. The C.T.s have a ratio of 1000/5. What % of the winding is protected ? What should be the value of resistance to get 90 % protected ?* **(Ans. : 65.3589 %, R = 2.8867 Ω)**

4.7 Unrestricted Earth Fault Protection

AU : May-05

The unrestricted earth fault protection uses a residually connected earth fault relay. It consists of three C.T.s, one in each phase. The secondary windings of these C.T.s are connected in parallel. The earth fault relay is connected across the secondaries which carries a residual current. The scheme is shown in the Fig. 4.7.1.

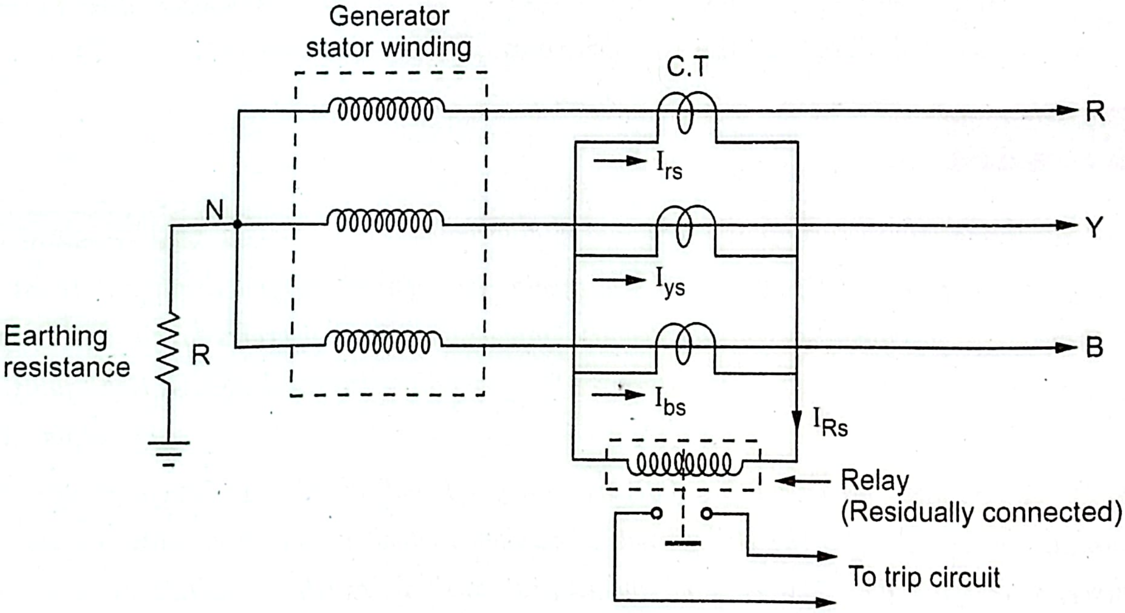


Fig. 4.7.1 Unrestricted earth fault protection

When there is no fault, under normal conditions, vector sum of the three line currents is zero. Hence the vector sum of the three secondary currents is also zero.

So if I_{rs}, I_{ys} and I_{bs} are C.T. secondary currents then under normal conditions we can write,

$$\bar{I}_{rs} + \bar{I}_{ys} + \bar{I}_{bs} = 0$$

The sum of the three currents is residual current I_{Rs} which is zero under normal conditions.

The earth fault relay is connected in such a way that the residual current flows through the relay operating coil. Under normal condition, residual current is zero so relay does not carry any current and is inoperative. However in presence of earth fault condition, the balance gets disturbed and the residual current I_{RS} is no more zero. If this current is more than the pickup value of the earth fault relay, the relay operates and opens the circuit breaker through tripping of the trip circuit.

In the scheme shown in the Fig. 4.7.1, the earth fault at any location near or away from the location of C.T.s can cause the residual current. Hence the protected zone is not definite. Such a scheme is hence called **unrestricted earth fault protection.**

Review Question

1. *Explain the operation of unrestricted earth fault protection scheme.* **AU : May-05, Marks 8**

4.8 Balanced Earth Fault Protection

In practice for small rating alternators, the neutral ends of the three phases are connected to a single point. Hence it is not possible to introduce C.T. in each phase on neutral side as required in Merz-Price protection. In such cases, the balanced earth fault protection can be used.

The balanced earth fault protection is shown in the Fig. 4.8.1.

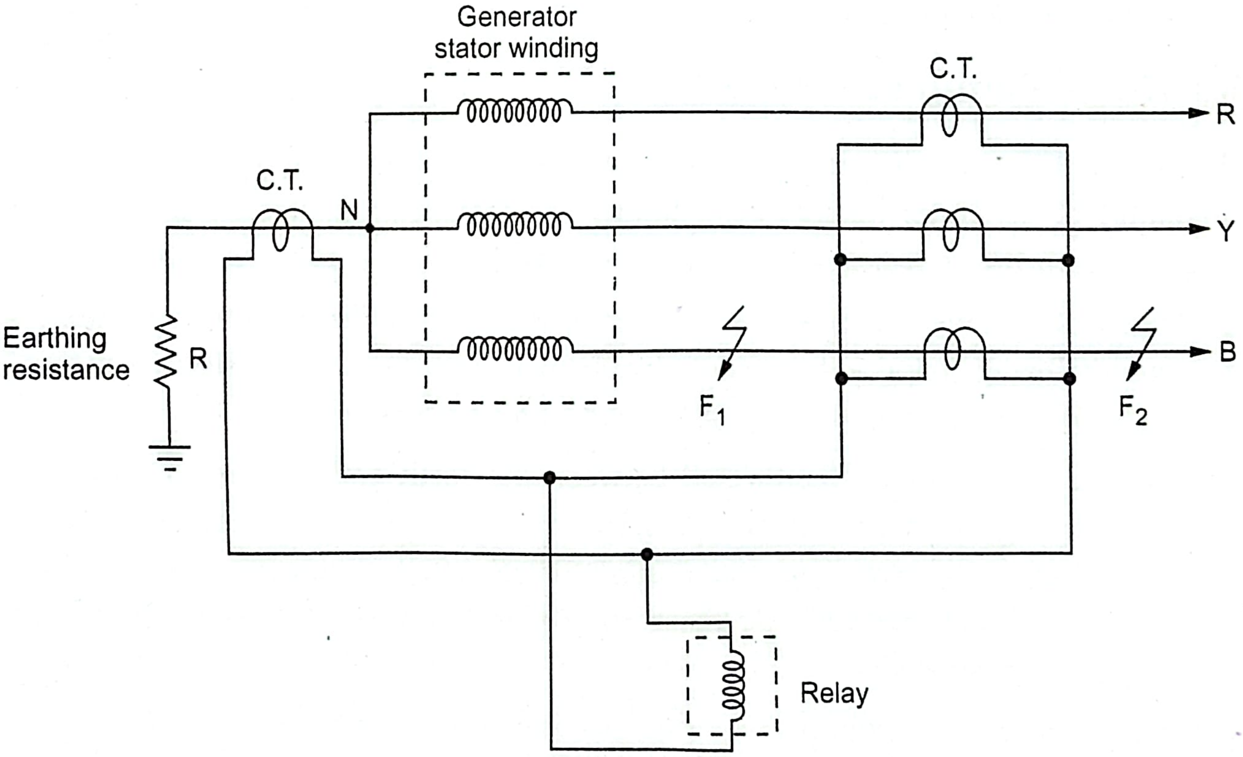


Fig. 4.8.1 Balanced earth fault protection

At the outgoing side, the three C.T.s are connected in parallel as are connected in unrestricted earth fault protection. A single C.T. is connected on the neutral side in the pilot wire connecting neutral of alternator to earth. The neutral earthing is achieved through the earthing resistance. A relay is connected across the C.T. secondaries.

Under normal conditions, the alternator line currents add to zero. Hence the vector sum of the currents through the secondaries of C.T. is also zero. Thus no current flows through the relay and as neutral carries zero current hence no current is supplied to relay from neutral side. So relay is inoperative.

If the fault appears at F_2, at a position outside the protected zone then the sum of the alternator line currents is exactly equal to the current in the neutral. Thus zero current flows through the relay is inoperative.

But if the fault occurs at F_1 which is the protected zone then vector sum of alternator line currents is different than the current through neutral side current transformer. Hence a residual current flows through the relay. If this is greater than the pickup value of the relay, the relay operates. This trips the tripping circuit, opening the circuit breaker.

By this scheme, the protection against earth faults is restricted to the region between the neutral and the position where line current transformers are installed.

Review Question

1. *Draw and explain balanced earth fault protection scheme.*

4.9 100 % Earth Fault Protection

As seen uptill now, no protection scheme is in a position to give complete protection to the stator of generator against earth faults. The maximum protection achieved is upto 85 to 90 % from the schemes discussed uptill now.

But in modern days it is possible to provide 100 % earth fault protection to the stator of the generator. It uses a coupling transformer and the coded signal current. The scheme is shown in the Fig. 4.9.1. (See Fig. 4.9.1 on next page)

A coupling transformer is connected between the earth and the earthing resistance R i.e. in neutral to ground circuit. The primary of the coupling transformer is excited by coded signal current source. This coded signal current has a frequency of 12.5 Hz. This current is continuously injected into the generator stator winding through the secondary of the coupling transformer.

During the normal condition the signal current injected into the stator flows through stray capacitance of the generator and directly connected system. But when earth fault occurs, the stray capacitance is bypassed. This increases the monitoring current. This

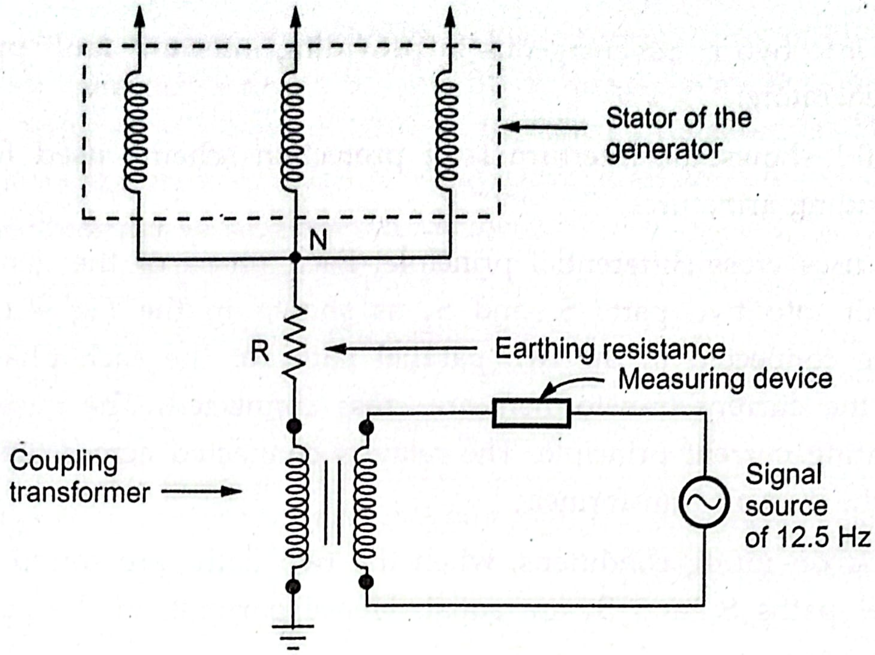


Fig. 4.9.1 100 % earth fault protection

increase is measured by a measuring device. Depending upon this measurement an immediate corrective action is taken.

This scheme gives the protection of 15 to 20 % of stator winding from the neutral side, the portion which is unprotected by Merz-Price protection. The remaining portion is protected by Merz-Price protection. Overall 100 % of stator winding gets protected against earth faults.

Review Question

1. *Is it possible that 100 % winding of generator is protected against earth faults ? How ?*

4.10 Stator Protection against Interturn Faults

May-12, 15, Dec.-12

The Merz-Price protection system gives protection against phase to phase faults and earth faults. It does not give protection against interturn faults. The interturn fault is a short circuit between the turns of the same phase winding. Thus the current produced due to such fault is a local circuit current and it does not affect the currents entering and leaving the winding at the two ends, where C.T.s are located. Hence Merz-Price protection cannot give protection against interturn faults.

In single turn generator, there is no question of interturn faults but in multiturn generators, the interturn fault protection is necessary. So such interturn protection is provided for multiturn generators such as hydroelectric generators. These generators have double winding armatures. This means, each phase winding is divided into two halves, due to the very heavy currents which they have to carry. This splitting of single phase winding into two is advantageous in providing interturn fault protection to such hydroelectric generators.

The Fig. 4.10.1 shows the interturn fault protection scheme used for the generator with double winding armatures.

The scheme uses cross differential principle. Each phase of the generator is doubly wound and split into two parts S_1 and S_2 as shown in the Fig. 4.10.1. The current transformers are connected in the two parallel paths of the each phase winding. The secondaries of the current transformers are cross connected. The current transformers work on circulating current principle. The relay is connected across the cross connected secondaries of the current transformers.

Under normal operating conditions, when the two paths are sound then currents in the two parallel paths S_1 and S_2 are equal. Hence currents in the secondaries of the current transformers are also equal. The secondary current flows round the loop and is same at all the points. Hence no current flows through the relay and the relay is inoperative.

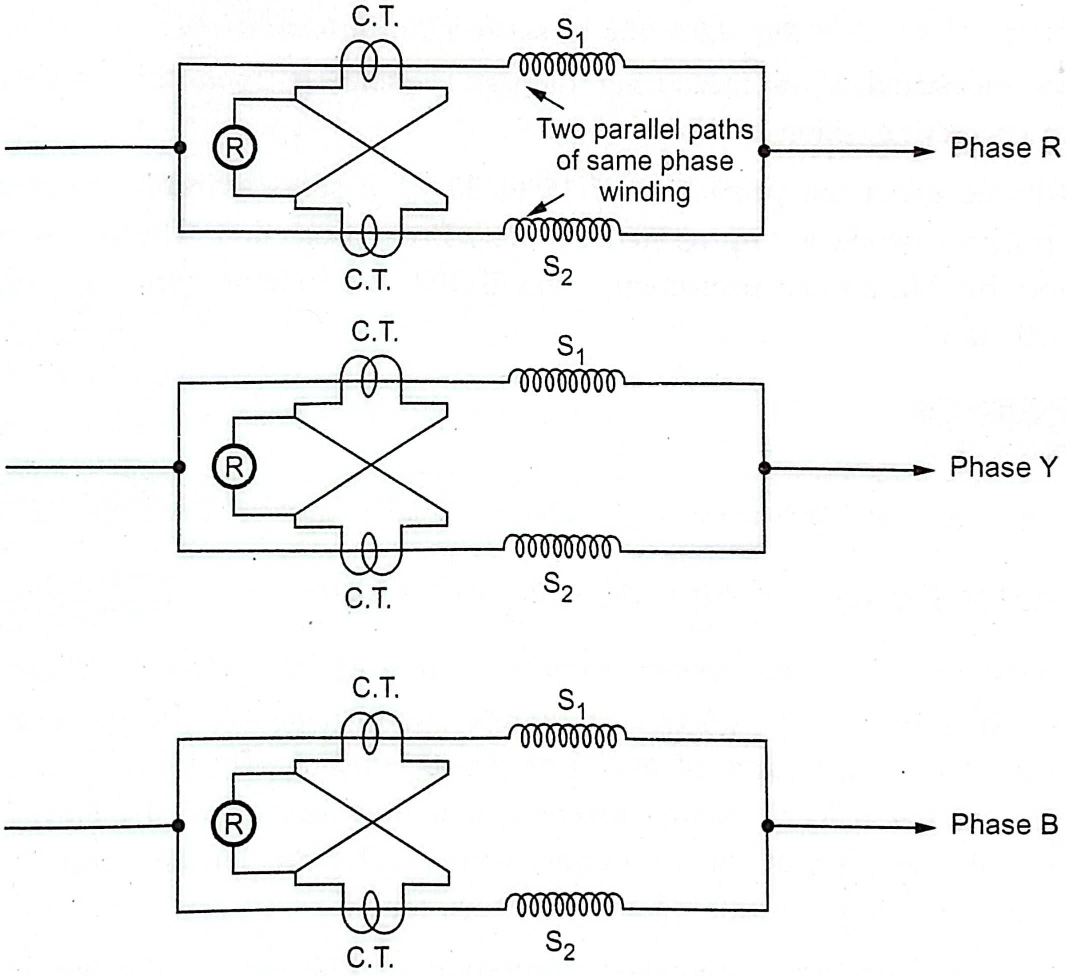


Fig. 4.10.1 Interturn fault protection

If the short circuit is developed between the adjacent turns of the part S_1 of the winding say then currents through S_1 and S_2 no longer remain same. Thus unequal currents will be induced in the secondaries of the current transformers. The difference of these currents flows through the relay R. Relay then closes its contacts to trip the circuit breaker which isolates the generator from the system.

Such an interturn fault protection system is extremely sensitive but it can be applied to the generators having doubly wound armatures.

Review Questions

1. *Explain a protection scheme for stator interturn faults of a generator.*

   AU : May-12, Dec.-12, Marks 10

2. *Briefly explain the various types of stator fault protections of alternator.*

   AU : May-15, Marks 16

4.11 Rotor Earth Fault Protection

The rotor circuit of the alternator is not earthed and d.c. voltage is imposed on it. And hence single ground fault in rotor does not cause circulating current to flow through the rotor circuit. Hence single ground fault in rotor does not cause any damage to it. But single ground fault causes an increase in the stress to ground at other points in the field winding when voltages are induced in the rotor due to transients. Thus the probability of second ground fault increases.

If the second ground fault occurs then part of the rotor winding is bypassed and the currents in the remaining portion increase abruptly. This causes the unbalance of rotor circuit and hence the mechanical and thermal stresses on the rotor. Due to this, rotor may get damaged. Sometimes damage of bearings and bending of rotor shaft takes place due to the vibrations. Hence the rotor must be protected against earth fault.

Method 1 : In this method a high resistance is connected across the rotor circuit. It is provided with centre tap and the centre tap point is connected to the ground through a sensitive earth fault relay as shown in the Fig. 4.11.1.

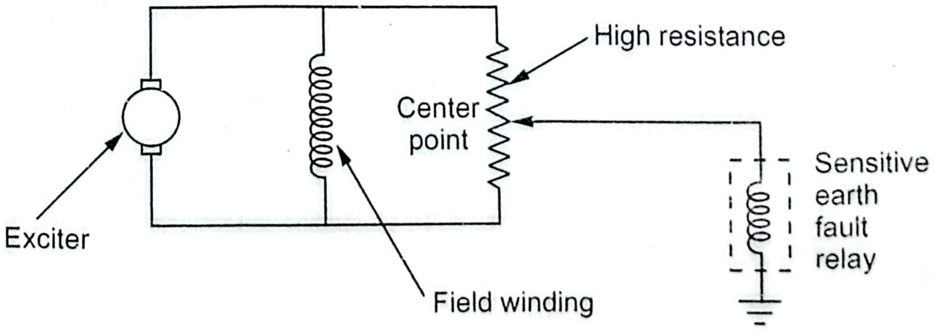


Fig. 4.11.1 Rotor earth fault protection

Except the centre point, the earth fault relay detects the earth faults for most of the rotor circuit. Thus most of the rotor winding part is protected against the earth faults.

Method 2 : The modern method of providing earth fault protection includes d.c. injection or a.c. injection. The scheme is shown in the Fig. 4.11.2.

A small d.c. power supply is connected to the field circuit. A fault detecting sensitive relay and the resistance are also connected in series with the circuit. This high resistance limits the current through the circuit.

A fault at any point on the field circuit will pass a current of sufficient magnitude through the relay to cause its operation. The d.c. supply is preferred and simple to use and it has no problem of the leakage currents. In case of a.c. injection, the high resistance is replaced by a capacitor.

The earth fault relays are instantaneous in operation and are connected to an alarm circuit for indication and to take the proper action. This is because, a single ground fault does not require an immediate action of isolating the generator.

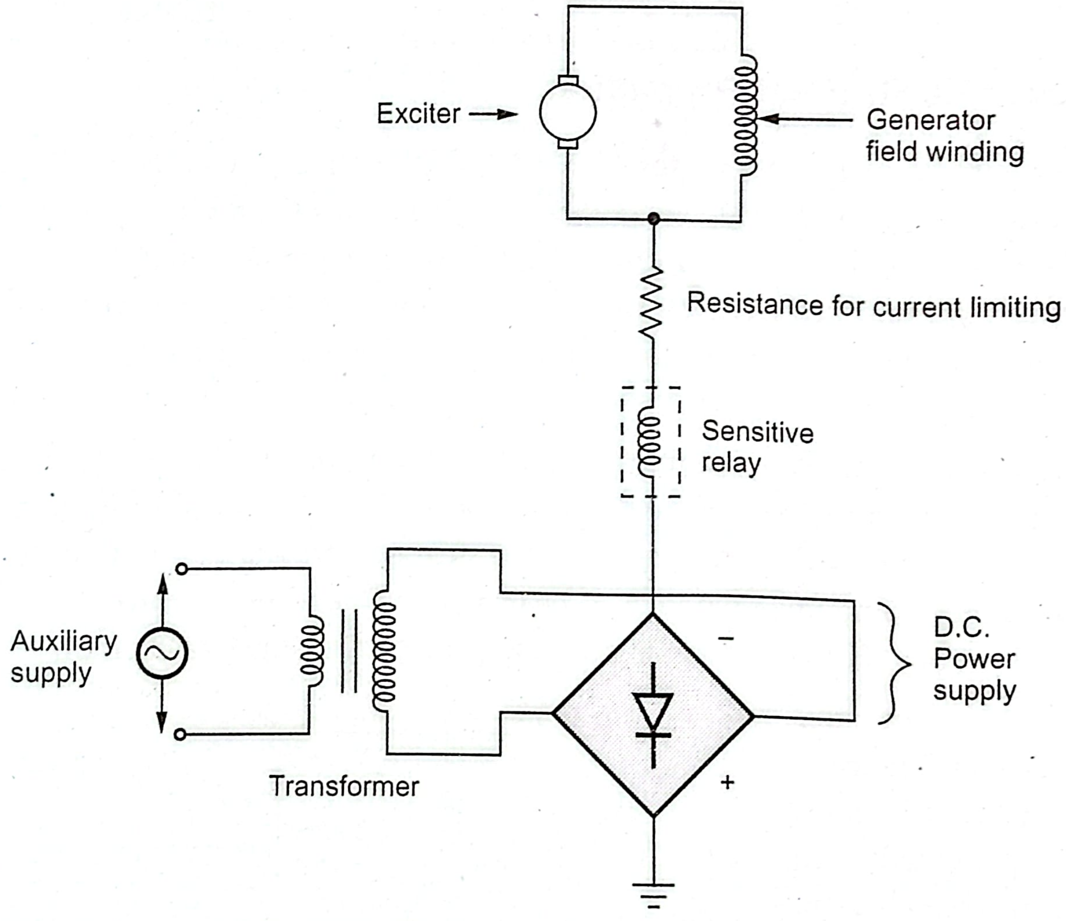

Exciter
Generator field winding
Resistance for current limiting
Sensitive relay
Auxiliary supply
Transformer
−
+
D.C. Power supply

Fig. 4.11.2 Rotor earth fault protection

Review Question

1. *What are the methods to provide rotor earth fault protection ?*

4.12 Protection against Loss of Excitation (Field Failure)

AU : May-08,22, Dec.-12

The loss of excitation of the generator may result in the loss of synchronism and slightly increase in the generator speed. The machine starts behaving as an induction generator. It drawn reactive power from the system which is undesirable. The loss of excitation may lead to the pole slipping condition. Hence protection against loss of excitation must be provided.

The protection is provided using directional distance type relay with the generator terminals.

When there is loss of excitation, the equivalent generator impedance varies and traces a curve as shown in the Fig. 4.12.1. This Fig. 4.12.1 shows the loss of excitation characteristics along with the relay operating characteristics, on R-X diagram.

The equivalent generator impedance locus traces a path from first quadrant of R-X diagram to the fourth quadrant. The distance relay is used which covers the portion of the fourth quadrant where impedance locus path exists. Thus when the impedance takes value in the region covered by the relay characteristics, the relay operates. The relay operates when generator first starts to slip poles. Then relay trips the field circuit breaker. And it disconnects the generator from the system, too. When the excitation is regained and becomes normal, the generator can then be returned to service instantly.

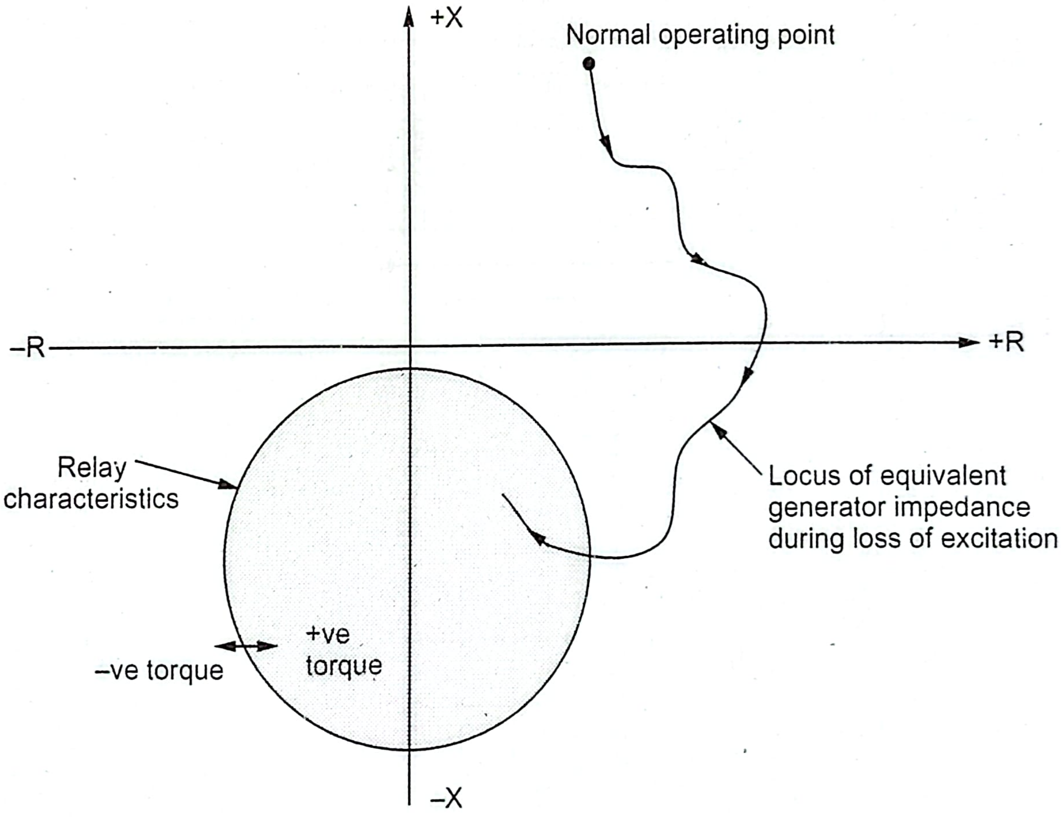


Fig. 4.12.1 Loss of excitation characteristics

Review Questions

1. *Describe the loss of excitation protection in a generator and its characteristics.* **AU : Dec.-12, May-22, Marks 8**
2. *What are the rotor faults and explain protection schemes for them.* **AU : May-08, Marks 16**

4.13 Detection of Turn-Turn Fault

The inter-turn fault does not disturb the balance between the currents in neutral and high voltage C.T.s. Hence the longitudinal differential protection can not be used. The scheme used for detecting turn-turn fault is shown in the Fig. 4.13.1.

When there is turn to turn fault, then zero sequence voltage appears across the tertiary winding of the potential transformer. This winding is connected to the operating winding of watthour meter type three element directional relay. The zero sequence voltage energizes the operating relay winding and operates the relay to detect the turn to turn fault.

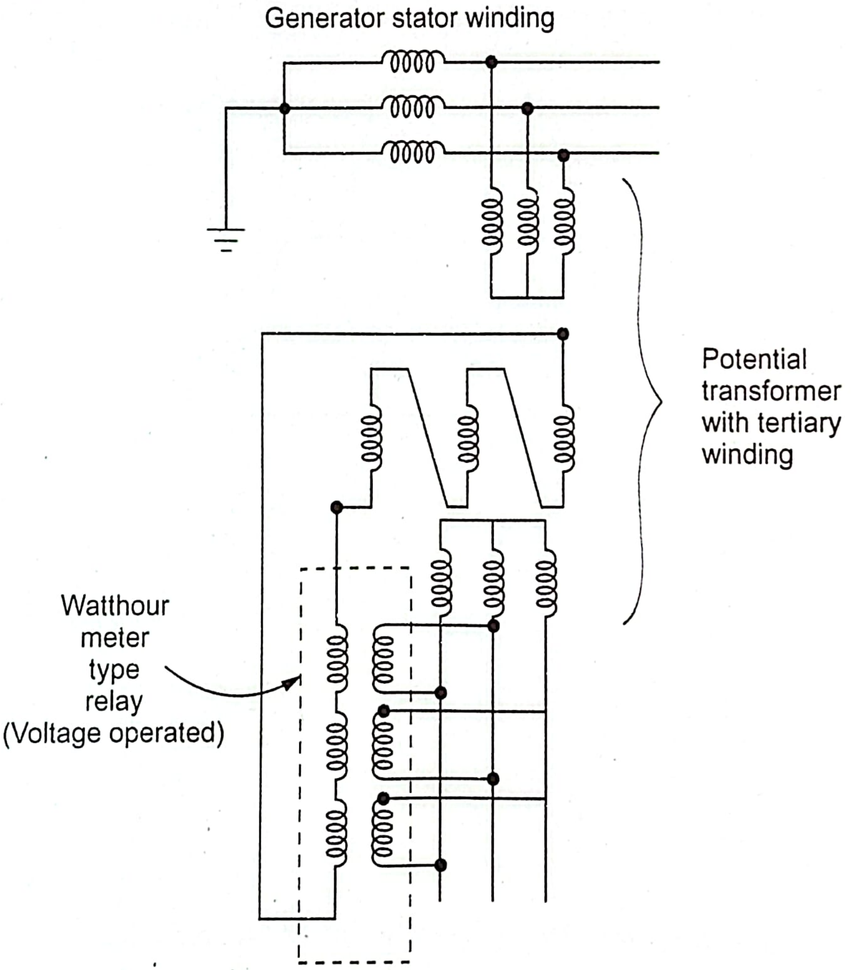

Generator stator winding
Potential transformer with tertiary winding
Watthour meter type relay (Voltage operated)

Fig. 4.13.1 Scheme for detecting turn to turn fault

Review Question

1. *Explain the scheme for detection of turn to turn fault.*

4.14 Negative Sequence Protection

AU : May-04

When the load on the generator becomes unbalanced, negative phase sequence currents flow. The negative sequence components produce a rotating magnetic field which rotates at synchronous speed in a direction opposite to the direction of rotor field. Hence effectively the relative speed between the two is double the synchronous speed. Thus double frequency currents are induced in the rotor. These currents cause severe heating of the rotor and can cause damage to the rotor. The unbalanced stator currents also cause severe vibrations and heating of stator. Hence it is necessary to provide the negative sequence protection to the generators against the unbalanced load conditions.

The negative phase sequence filter alongwith the overcurrent relay provides the necessary protection against the unbalanced loads.

The relative asymmetry of a three phase generator is given by the ratio of negative sequence current to the rated current. Mathematically it can be expressed as,

$$\% S = \frac{I_n}{I} \times 100$$

where $\% S$ = Percentage asymmetry

I_n = Negative sequence current

I = Rated current

The negative sequence protection scheme is shown in the Fig. 4.14.1.

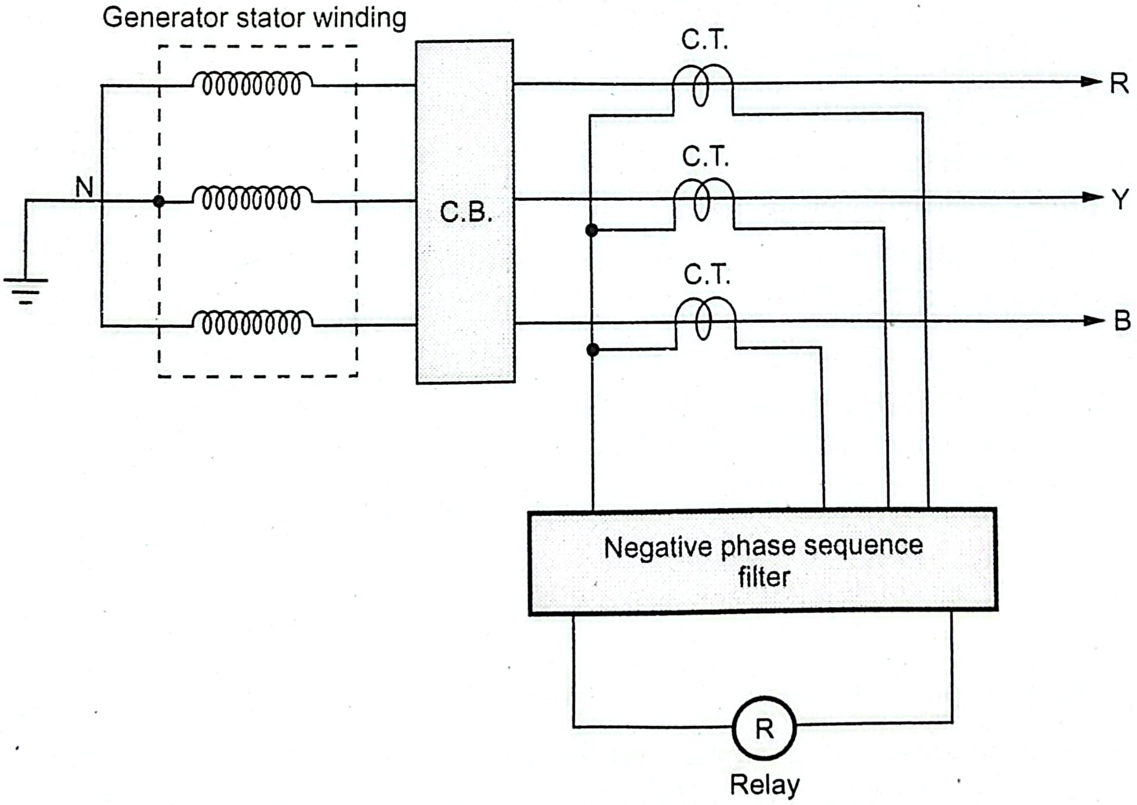


Fig. 4.14.1 Negative sequence protection

A negative phase sequence filter is connected to the secondaries of the current transformers. A negative phase sequence filter consists of resistors and inductors. These are so arranged that under normal operating conditions, the relay is inoperative. The filter circuit is stable for the symmetrical overloads up to about three times the rated full load.

When unbalanced load occurs, the negative phase sequence filter circuit produces an output proportional to the negative phase sequence components. This is directed through the relay coil. Hence the relay operates to open the circuit breaker to isolate the generator.

Review Question

1. *Explain the negative sequence protection of alternators.* **AU : May-04, Marks 8**

4.15 Reverse Power Protection (Loss of Prime Mover Protection)

The prime movers of alternators are the turbines. When the input to the turbine is stopped, it is called loss of prime mover condition. This results into motoring action of generator and it draws an active power from the busbar. This is reverse power flow which is generally of the order of 2 to 10 % of the rated power. Such a reverse power flow is dangerous if persists for more than twenty seconds.

In steam turbines, reverse power flow overheats the blades. While the gas turbines offer a load of 10 to 50 % of full load during motoring hence reverse power flow is dangerous. Motoring is also harmful to the prime movers like reciprocating engines and hydraulic turbines. Hence reverse power protection is used in generators.

During the reverse power flow, the three phase conditions are balanced in nature. Thus a single element directional power relay used in any one phase is sufficient to provide the protection.

The Fig. 4.15.1 shows the characteristics of such a directional power relay. The setting of such a relay depends on the type of the prime mover.

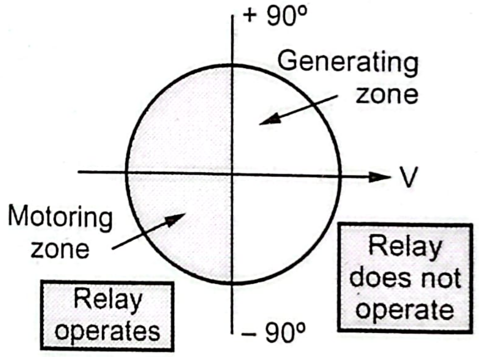


Fig. 4.15.1 Characteristics of reverse power protection

The factors to be considered for designing such reverse power protection are,

1. Capability of prime mover to run as a load.
2. Load current drawn by generator while working as a motor.

Generally reverse power protection is set for 10 % of rated power flowing in reverse direction.

Review Question

1. *Discuss the protection of alternators in the event of loss of prime mover.*

4.16 Introduction to Motor Protection

Based on the control action i.e. starting, stopping or reversal, various controlling elements known in electrical terms as switchgear are employed for the protection of induction motor. Generally two basic protections viz. short circuit protection and overload protection are provided for each motor. The switchgear used for protection includes contactors with H.R.C fuse and thermal overload relays along with circuit breakers.

If the rating of the motor is upto 150 kW then contactors and fuses can be used while for motors having rating beyond 150 kW, circuit breakers are used. The contactor is a kind of switch through which supply can be given to the motor when its coil is energized. If the current to be interrupted is six times the rated current of the motor then contactors can be used.

4.17 Abnormal Conditions and Failure in Case of Induction Motor

The three phase induction motors are used in numerous industrial applications. Hence before studying the protection circuit we have to consider the abnormal conditions and failure that may occur in case of induction motor.

If the motor is heavily loaded beyond its capacity then it will be overload condition of motor in which case motor draws heavy current from the supply and there will be simultaneous rise in temperature of winding and deterioration of the insulation resulting in damage of winding. Hence the motor must be protected against this mechanical overloading with overload protection circuits. Normally thermal overload relays, over current relays or miniature circuit breaker with built-in trip coils may be used.

It might be possible that the rotor is locked or starting lasts for longer duration or rotor does not move because of excessive load (stalling) at start. In all these cases motor draws heavy current from the supply and results in damage to the winding due to overheating as stated above. In this case thermal relays or instantaneous overcurrent relays are used.

If the supply conditions are abnormal such as loss of supply voltage, unbalanced supply voltage, phase sequence reversal of supply voltage, over voltage, under voltage or under frequency then also the performance of the motor is affected. With unbalanced supply voltage there will be excessive heating while with undervoltage the motor draws more current for the same load. For undervoltage protection, undervoltage relays are used.

With correct phase sequence, the motor runs in one direction. With change in phase sequence of supply it runs in other direction which is dangerous in some of the applications such as cranes, hoists or elevators. In such cases phase reversal relay may be provided which will disconnect the supply to the motor through the circuit breaker.

Due to excessive temperature rise, the insulation may get damaged which may lead to stator earth fault or stator phase to phase fault which are rare in nature. For low rating motors, HRC fuses provide sufficient protection against these faults while for large motors, differential protection may be used.

Due to blowing of fuse in any phase or open circuit in one of the three phases results in single phasing. In such case motor continues to run and if it is loaded to its rated value then it will draw excessive current which will damage the rotor and eventually the motor will be damaged due to excessive overheating. Normally thermal overload relays are used against single phasing. Sometimes special single phase preventer may be provided.

Summary of abnormal condition and protection circuit to be employed is given in the Table 4.17.1.

Sr. No.	Abnormal condition	Choice of protection circuit to be employed
1.	Mechanical overload.	Overload release, thermal overload relay, over current relays, Miniature Circuit Breaker (MCB) with built-in trip coil.
2.	Stalling or prolonged starting of motor.	Thermal relays, instantaneous overcurrent relay.
3.	Under voltage.	Under voltage release, under voltage relay.
4.	Unbalanced voltage.	Negative phase sequence relays.
5.	Reverse phase sequence.	Phase reversal relay.
6.	Phase to phase fault or phase to earth fault.	HRC fuse, instantaneous overcurrent relays. For large motors, differential protection may be employed for economy.
7.	Single phasing.	Thermal overload relays, single phase preventer.

Table 4.17.1

The motor protection circuit that is designed should be simple in operation and economically feasible. Its cost should be less than 5 % of the motor cost. It should also be kept in mind that during starting and permissible overload conditions, the protection circuit should not operate. The choice of motor protecting circuit is based on various factors such as rated voltage, rated kW, size of motor, type of induction motor, type of starter, type of switchgear used, cost of motor, type of load, starting current possibility of occurrence of abnormal conditions etc.

Review Question

1. *List the various abnormal operating conditions against which a large induction motor has to be protected.*

4.18 Protection Circuit for Induction Motor

AU : Dec.-06,16,22, May-18

The protection circuit along with its single line diagram is shown in the Fig. 4.18.1.

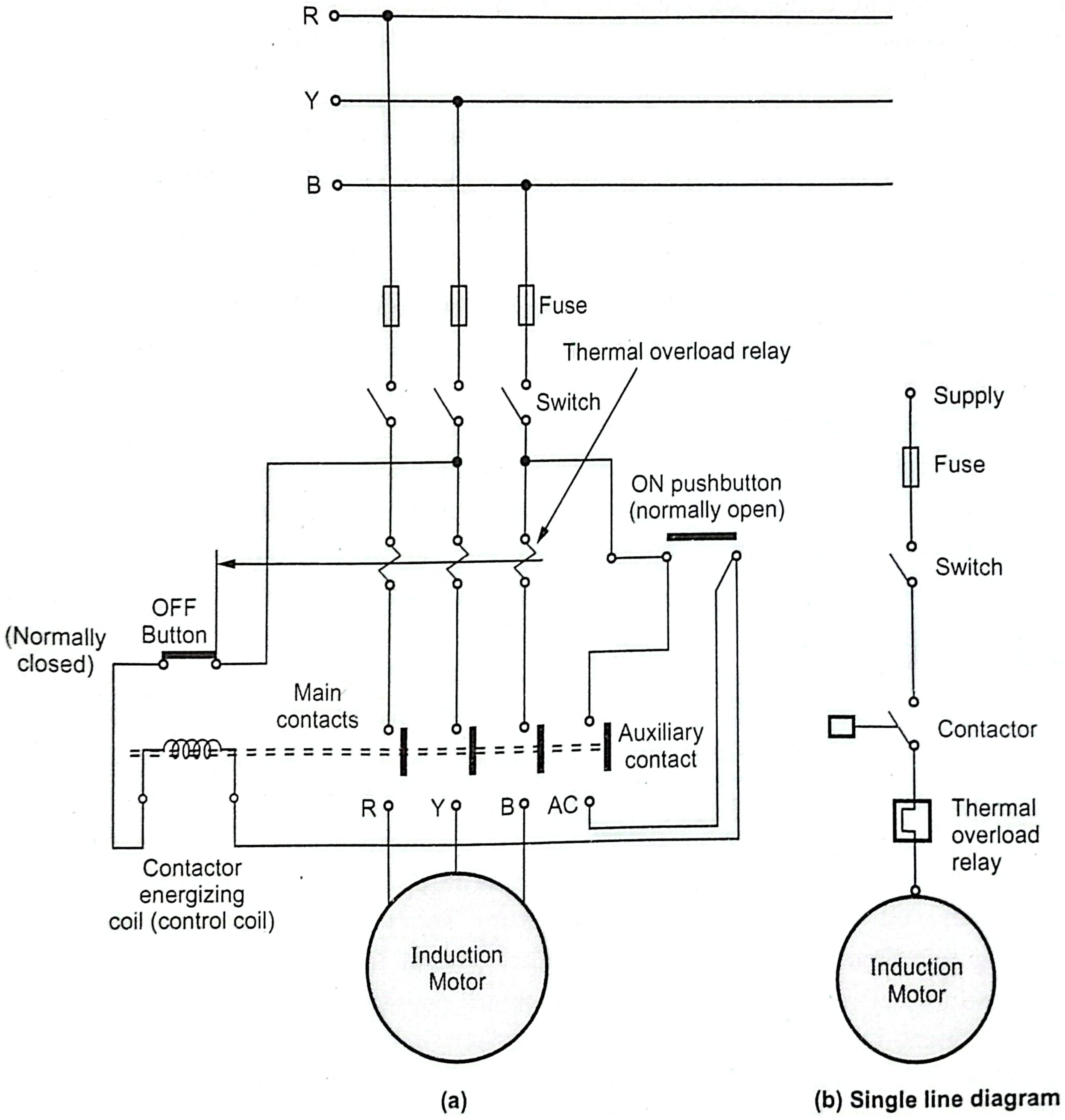

R
Y
B
Fuse
Thermal overload relay
Switch
ON pushbutton
(normally open)
OFF
Button
(Normally
closed)
Main
contacts
Auxiliary
contact
R
Y
B
AC
Contactor
energizing
coil (control coil)
Induction
Motor
(a)
Supply
Fuse
Switch
Contactor
Thermal
overload
relay
Induction
Motor
(b) Single line diagram

Fig. 4.18.1

The three phase supply is given to the motor through various elements such as fuse, switch, contactor and thermal overload relay. The control circuit of contactor consists of energizing coil, start and stop buttons. The start (ON) push button is normally open green switch while the stop (OFF) push button is normally closed red switch.

When the start button is pressed then the contactor coil is energized as it gets supply voltage. The coil attracts the plunger when excited and the main contacts are closed along with the auxiliary contact. Even if the ON push button is released, the contactor coil remains energized as it gets supply through auxiliary contacts. Thus motor starts running.

The OFF push button which is normally closed when pressed cuts the supply of the contactor coil and hence the main as well as auxiliary contacts are open so motor eventually stops. If supply voltage fails, control coil is de-energized which opens the contactor and motor stops.

During overload condition, the thermal overload relay operates. Thermal overload relay consists of bimetallic strips. Because of bending of one or more bimetallic strip results in operation of common lever which operates the trip contacts to de-energize the coil and disconnects the supply to the motor.

The bimetallic strips are either heated directly by flow of current or with the help of special heater coil through which motor current flows. For large motors, these relays are connected in secondary of current transformers. The bimetallic strips can be of self setting type or hand resetting type in which mechanical reset is required as the trip mechanism locks itself in operated condition. It should be observed that the rating of thermal relay should be such that it should not operate during normal starting conditions. A setting range is provided for adjustment for various load conditions. Protection against short circuit is provided with the help of HRC fuses.

Review Questions

1. *Explain the general induction motor protection scheme.* **AU : Dec.-06,16, May-18, Marks 8**
2. *Write a detailed note on motor protection with neat sketch.* **AU : Dec.-22, Marks 13**

4.19 Single Phasing Preventer

If one of the supply line is disconnected due to open circuit or improper contact in switch then still the motor continues to run. The power is then supplied to the remaining windings. The current in the other phases increases to about $\sqrt{3}$ times its normal value. This is called single phasing which results in unbalanced stator currents. The component which is present in this unbalanced current called negative sequence component causes magnetic flux rotating in opposite direction to the main flux. This results in double frequency currents to induce in the rotor to cause its heating. Thus major damage to motor may take place due to single phasing if proper precaution is not taken. As the phase overcurrent relays react slowly, they cannot give the instantaneous protection against single phasing.

For small motors separate protection against single phasing is normally not provided as thermal relays sense the increased current in remaining phases due to single phasing and provides the sufficient protection.

A separate single phasing protection circuit is required in case of large induction motors as even a small unbalance can cause damage to motor winding and rotor. The single phasing preventer is shown in the Fig. 4.19.1.

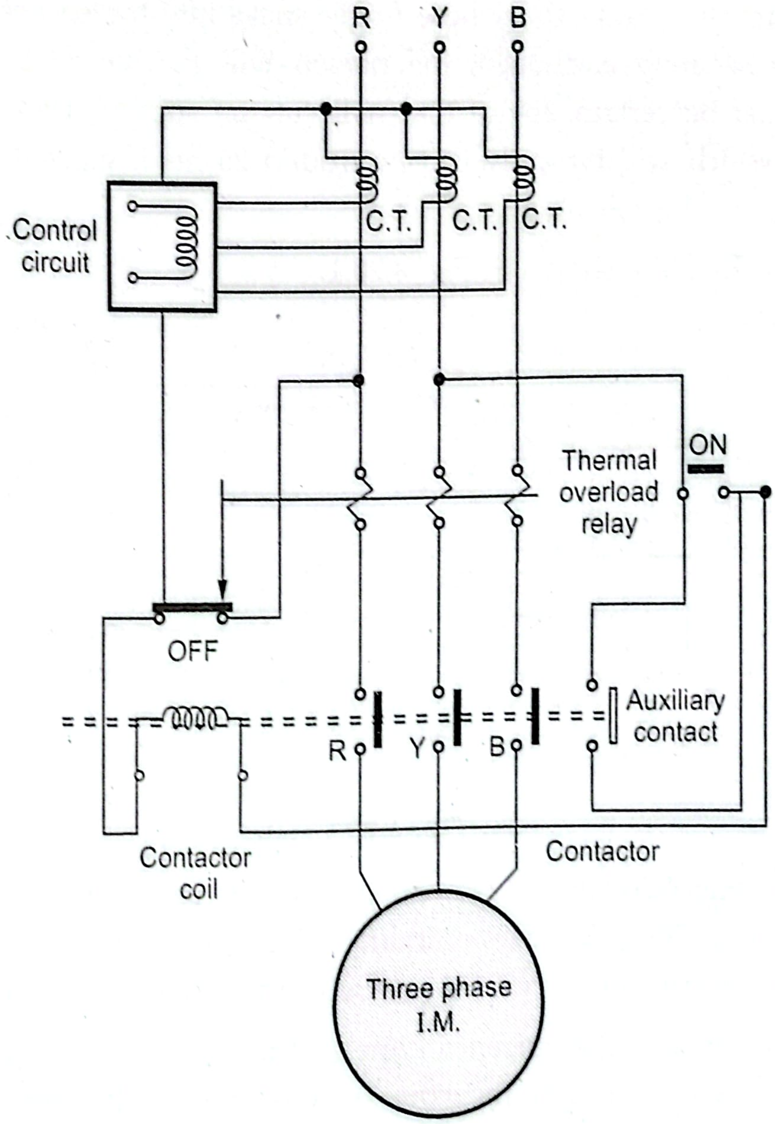

R
Y
B
C.T.
C.T.
C.T.
Control circuit
Thermal overload relay
ON
OFF
Auxiliary contact
R
Y
B
Contactor coil
Contactor
Three phase I.M.

Fig. 4.19.1

As shown in the Fig. 4.19.1, it consists of C.T.s connected in each phase. The output of control circuit is fed to the level detector which sense the magnitude of unbalance. Depending on this output from the control circuit the tripping command to the starter or the circuit breaker is given when negative sequence current exceeds its preset limit.

Review Question

1. *Explain single phasing preventer used for induction motor.*

4.20 Ground Fault Protection

The ground fault protection is achieved using Earth Leakage Circuit Breaker (ELCB). When the fault current or leakage current flows through earth return path then it forms the earth fault. These faults are relatively frequent and hence protection is required against these which is provided with the help of earth leakage circuit breaker.

Consider an example of a person whose finger sticks into the socket. Even though the metal enclosure is securely earthened, the person will receive a severe shock. Under such case there must be certain device that will cut the supply. This can be done with the help of ELCB which will typically trip in around 25 ms if current exceeds its preset value.

The schematic of ELCB is shown in Fig. 4.20.1.

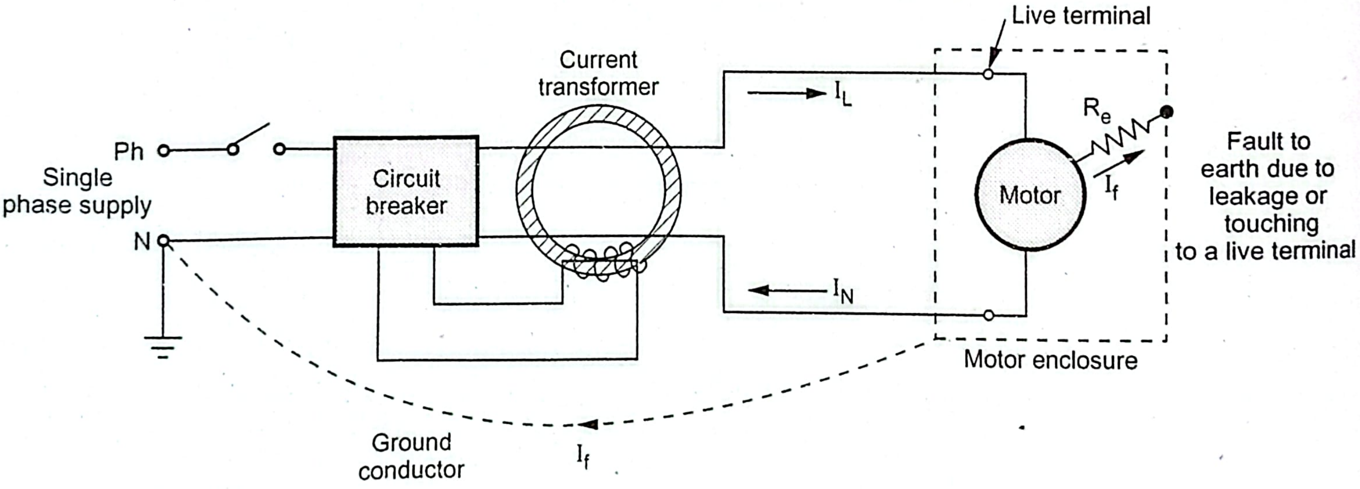


Fig. 4.20.1

As shown in the Fig. 4.20.1 ELCB consists of a small current transformer surrounding live and neutral wire. The secondary winding of current transformer is connected to relay circuit which can trip the circuit breaker which is connected in the circuit.

Under normal conditions, the current in line and neutral conductor is same so the net current $(I_L - I_N)$ flowing through the core is zero. Eventually there will not be any production of flux in the core and no induced e.m.f. So the breaker does not trip.

If there is a fault due to leakage from live wire to earth or a person by mistake touching to the live terminal then the net current through the core will no longer remain as zero but equal to $I_L - I_N$ or I_f which will set up flux and e.m.f. in C.T. As per the preset value the unbalance in current is detected by C.T. and relay coil is energized which will give tripping signal for the circuit breaker. As C.T. operates with low value of current, the core must be very permeable at low flux densities.

In case of three phase circuits, single ring shaped core of magnetic material, encircles the conductor of all three phases as shown in the Fig. 4.20.2. A secondary is connected to relay circuit. Under normal condition, the component of fluxes due to fields of three conductors are balanced and secondary carries negligible current.

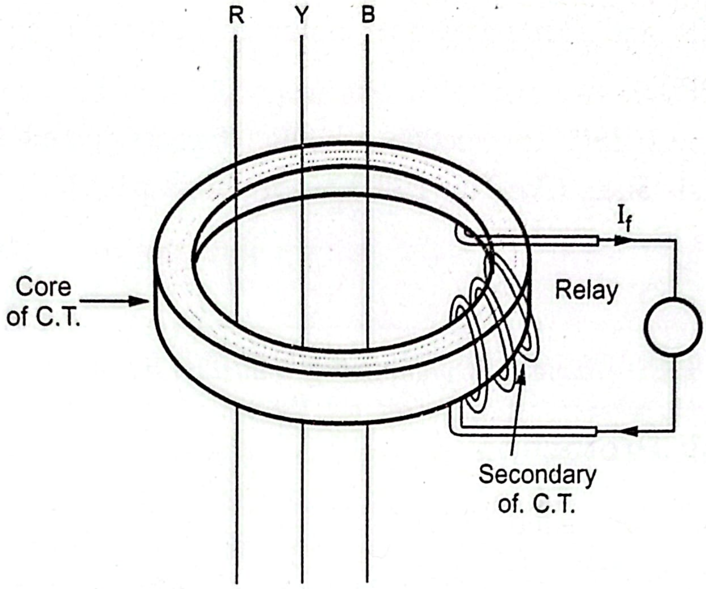

R
Y
B
I_f
Relay
Core of C.T.
Secondary of. C.T.

Fig. 4.20.2

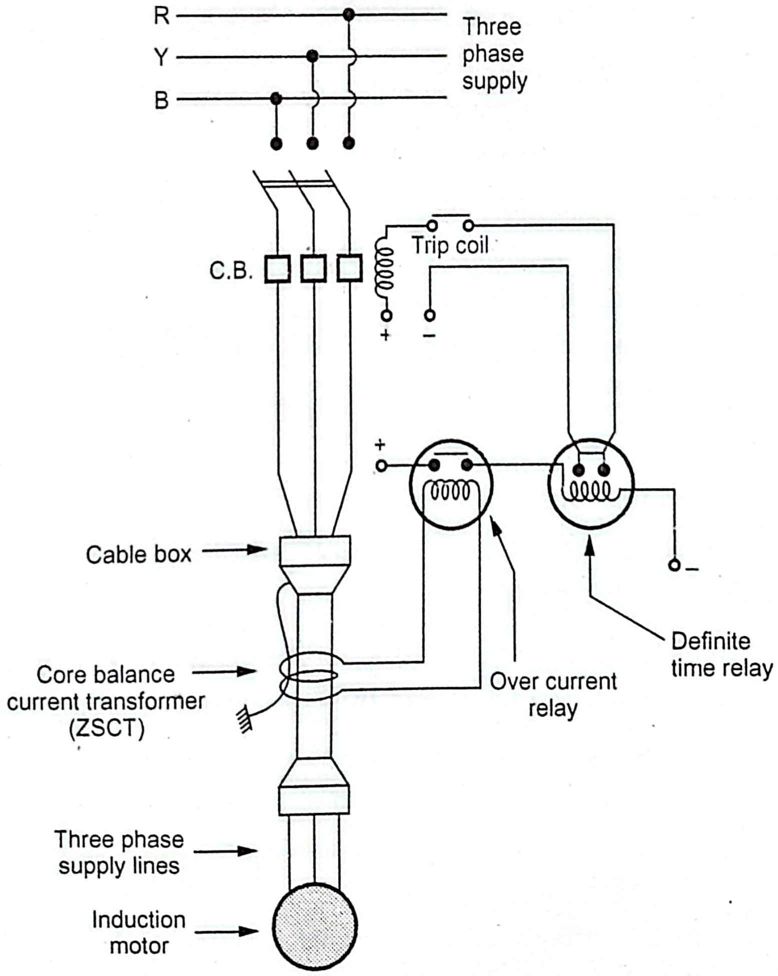

R
Y
B
Three phase supply
Trip coil
+
−
C.B.
+
Cable box
Core balance current transformer (ZSCT)
Over current relay
Definite time relay
−
Three phase supply lines
Induction motor

Fig. 4.20.3 Earth fault protection by ZSCT

During faulty condition, the balance is disturbed and current is induced in the secondary to trip the circuit breaker through relay.

This method to provide **earth fault protection** is called core balance type protection or **Zero Sequence Current Transformer** (ZSCT) protection. In case of earth faults, to avoid burning of coils and stampings the motor must be disconnected as quickly as possible from the supply.

The Fig. 4.20.3 shows ZSCT protection scheme. It is preferred for the systems with neutral earthed via resistance. (See Fig. 4.20.3 on previous page)

Review Question

1. *Draw and explain the ground fault protection of induction motor.*

4.21 Phase Fault Protection

This protection is also called short circuit protection. At the time of such a fault, the current increases by 8 to 10 times the full load current of the motor. Attracted armature type relay unit is connected in each phase with a current setting of 4-5 times the full load current. This is because starting current can be 4-5 times full load current. Hence to operate the relay only under fault condition such a setting is necessary. Such a protection is shown in the Fig. 4.21.1.

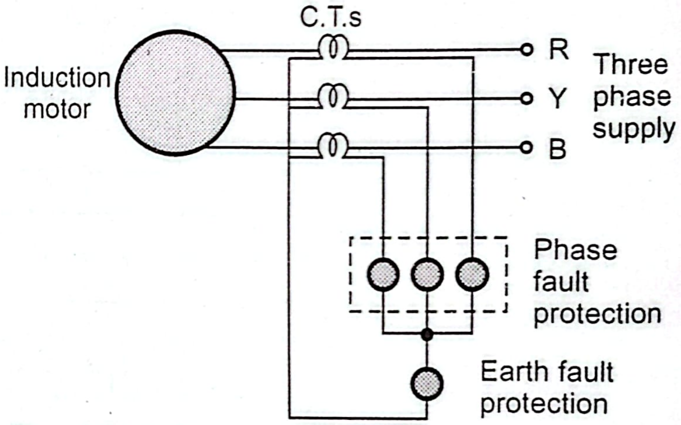


Fig. 4.21.1 Phase and earth fault protection

The phase faults can cause burn out of coils and stampings and hence motor should be disconnected as quickly as possible when fault occurs. Fast over current relays also are used to provide phase fault protection.

As mentioned above to avoid relay functioning during starting, the short circuit protection current setting must be just above the maximum starting current of the motor.

Review Question

1. *How phase faults protection is provided to the induction motors ?*

4.22 Phase Reversal Protection

The direction of induction motor depends on the direction of rotating magnetic field produced by the stator windings. For a particular phase sequence RYB the motor rotates in a particular direction due to corresponding direction of rotating magnetic field. But if any two lines are interchanged after repairs the phase sequence reverses such as YRB. Then the direction of rotating magnetic field also reverses and induction motor starts rotating in opposite direction. Such a change of direction is dangerous if the induction motor is used for cranes, hoists, lifts or in treading mills etc.

Thus to disconnect induction motor from supply if there is phase reversal, phase reversal protection is provided.

This protection is provided using motor driven disc working on electromagnetic principle. The secondaries of two current transformers connected in two lines drive the motor to operate the disc. The arrangement is such that for a normal direction of motor, disc rotates in a particular direction which keeps the auxiliary contacts closed. But if there is phase reversal then the torque produced reverses to rotate the disc in opposite direction. Due to this auxiliary contacts get opened. This inturn either operates the circuit breaker or de-energises starter coil to disconnect the motor from the supply. Thus phase reversal protection for the induction motor is achieved. Now a days solid state phase reversal relay sensing the phase reversal is used.

Review Question

1. *What is phase reversal ? What is its effect ? How it is prevented in induction motors ?*

4.23 Two Marks Questions with Answers

Q.1 What are the different faults that may occur in an alternator ?

AU : Dec.-10, May-13, 15

Ans. :

1. Stator faults : Phase to earth faults, phase to phase faults and inter-turn faults.
2. Rotor faults : Overheating of rotor due to unbalanced loading, rotor inter-turn faults, conductor to earth faults.
3. Abnormal running conditions such as overloading, overspeeding, unbalanced loading, overvoltage, failure of prime mover, loss of excitation and cooling system failure.

Q.2 What are the limitations of Merz-Price protection ? **AU : May-11**

Ans. : Since neutral earthing resistances are often used to protect circuit from earth-fault currents, it becomes impossible to protect the whole of a star-connected alternator. If an earth-fault occurs near the neutral point, the voltage may be insufficient to operate the relay. Also it is extremely difficult to find two identical CT's.

In addition to this, there always an inherent phase difference between the primary and the secondary quantities and a possibility of current through the relay even when there is no fault.

Q.3 State the advantages of Merz-Price protection method.

Ans. :
1. Very high speed of operation.
2. It allows low fault setting which ensures maximum protection of machine windings.
3. It ensures complete stability under the most severe through and external faults.
4. It does not require current transformers with air gaps or special balancing features.

Q.4 What is the need for negative sequence relay in alternators ? **AU : Dec.-05**

Ans. : When the load on the alternator becomes unbalanced, negative phase sequence currents flow. Such currents produce rotating magnetic field which rotates in opposite direction to the original rotating magnetic field. This produces the double frequency currents in the rotor which cause severe overheating of the rotor and can cause damage to the rotor. Hence the negative sequence relay is required to proved protection against the negative sequence currents.

Q.5 Draw the protection scheme to detect a turn-turn fault in an alternator.
(Refer section 4.13) **AU : Dec.-05**

Q.6 Draw the schematic diagram of biased differential protection scheme for alternators. **AU : May-06**

Ans. :

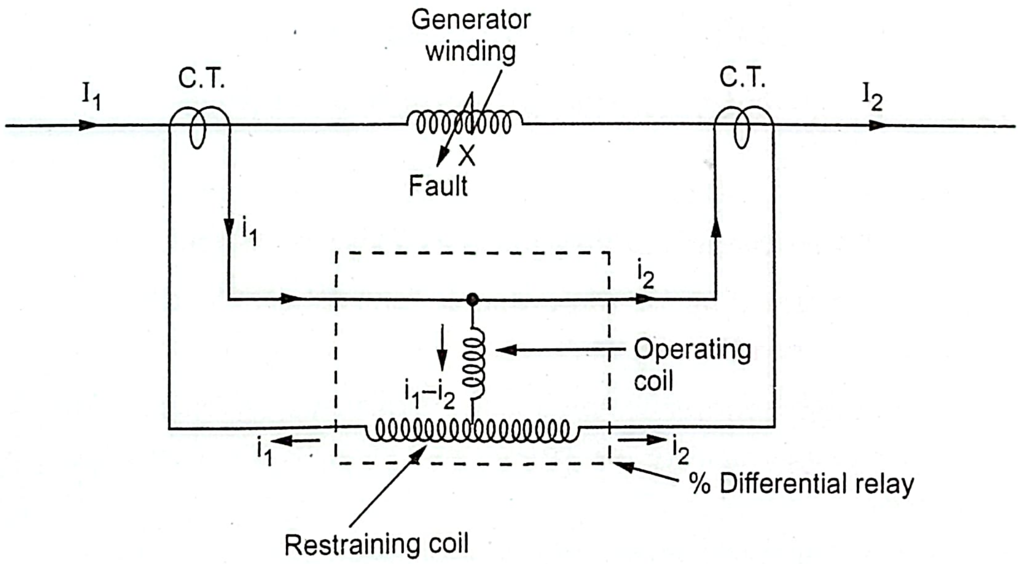


Fig. 4.23.1 Percentage differential protection scheme

Q.7 Why the protection of alternators is complex ? **AU : Dec.-08**

Ans. : 1. The alternators are very large machines producing very large voltages.

2. Various other equipments such as prime movers, excitation systems, voltage regulators, cooling systems etc. are associated with alternators which must be considered at the time of providing protection.

3. The alternators are very costly, expensive and important factor in a power system hence the protection scheme should be such that it should not shut off the alternators as far as possible.

Due to all these reasons the protection of alternators is complex.

Q.8 Discuss the problem arising due to failure of prime mover in generator.

Ans. : The failure of prime mover results in a motoring operation of a generator. The generator draws active power from the network and continues to run as a synchronous motor. This leads to dangerous mechanical conditions. It causes serious overheating of turbine blades.

Q.9 Why loss of excitation must be avoided in generators ?

Ans. : Loss of excitation in generators results in loss of synchronism which causes increase in the speed. Since the power input to the machine is same, the generator starts working as an induction generator and draws reactive power from the bus. The machine starts drawing an exciting current from the system which is almost equal to full load rated value which leads to overheating of the stator windings and the rotor body due to induced currents. The loss of excitation also leads to pole slipping condition which results in the voltage reduction. Hence the loss of excitation must be avoided.

Q.10 What is a restricted earth fault protection of alternators ?

Ans. : In alternator, a neutral is grounded using earthing resistance. The earth faults are rare near the neutral point as the voltage of neutral point with respect of earth is very less. But when earth fault occurs near the neutral point then the insufficient voltage across the fault drives very low fault current than the pick up current of the relay coil. Hence the relay coil remains inoperative. Thus about 15 to 20 % of the winding from the neutral side remains unprotected. Hence the scheme is called restricted earth fault protection.

Q.11 For a 13.2 kV generator, the rated current is 437.386 A. The relay setting is such that it trips for 20 % out of balance. If the earthing resistance is 13.068 Ω find the % of winding unprotected.

Ans. : $I_0 = 20\ \%$ of rated current $= 0.2 \times 437.386 = 87.477$ A

$$\%\ \text{Winding unprotected} = \frac{RI_0}{V} \times 100 = \frac{13.068 \times 87.477}{\frac{13.2}{\sqrt{3}} \times 1000} \times 100 = \mathbf{15}\ \%$$

Q.12 What is the cause of over speed and how alternators are protected from it ? **AU : May - 18**

Ans. : In case of alternators, a sudden loss of load results in rise in speed which is called over speeding of alternators. Generally alternator is provided with a mechanical over speed device i.e. speed governor which controls the speed. Also speed sensing device can take action such as operating the steam valve so as to stop steam input to the turbine to reduce the speed.

Q.13 In the event of faults in generator windings, field excitation is to be suppressed as early as possible. Why ? **AU : Dec.-18**

Ans. : In case of generators, opening a circuit breaker to isolate the faulty generator is not sufficient to prevent the damage. If the field is excited, the generator will continue to supply power to a faulty stator windings causing more damage. Hence it is necessary that the field excitation is to be suppressed. This is achieved by using automatic field suppression device.

Q.14 Why is overload protection not necessary for alternators ? **AU : May-22**

Ans. : Overload protection is not necessary for alternators because the chances of overloading faults on the alternators are negligible. The actual power generation depends on the prime mover which is continuously observed and regulated by governors and regulators. Also if overload protection is provided then for harmless momentary overloads, the alternator will be out of service causing blackouts and interruption of electric supply.

4.24 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *Draw and explain protection scheme of an A.C. induction motor.* **[Section 4.18]** **[16]**

Dec.-17

Q.2 *Give a brief account on the protection of generator using differential and biased differential protection scheme.* **[Sections 4.3 and 4.4]** **[16]**

May-18

Q.3 *With neat sketch explain the protection schemes for motors.* **[Section 4.18]** **[8]**

(Regulation 2017)

May-22

Q.4 *Discuss the protection employed against loss of excitation of an alternator.* **[Section 4.12]** **[13]**

Q.5 *Enumerate the relaying schemes which are employed for the protection of a modern alternator.* **[Sections 4.4 and 4.5]** **[15]**

Dec.-22

Q.6 *Write the detailed note on motor protection with neat sketch.* **[Section 4.18]** **[13]**

Q.7 *Explain about the following*

i) Faults occur in generator. **[Section 4.2]** **[6]**

ii) Merz-price protection of a generator. **[Section 4.5]** **[7]**

❑❑❑

UNIT III

5

Busbar and Transmission Line Protection

Syllabus

Protection of busbars and transmission line.

Contents

5.1 Busbar Protection .... **Dec.-06,13, May-14,18** · · · · Marks 8
5.2 Introduction to Feeder Protection
5.3 Overcurrent Protection of Transmission Lines
5.4 Nondirectional Time and Current Graded Protection
.... **May-11,** · · · · · · · · · · · · · · · Marks 8
5.5 Directional Time and Current Graded Protection
.... **May-06,13,** · · · · · · · · · · · · · Marks 6
5.6 Differential Protection of Feeders (Pilot Wire Protection)
.... **May-06,08,11,15,22,**
.... **Dec.-11,** · · · · · · · · · · · · · · Marks 16
5.7 Protection of Transmission Lines .... **Dec.-13,14, May-19** · · · · · Marks 16
5.8 Block Schematic of Carrier Aided Protection . . **May-15, Dec.-15,** · · · · · · · · Marks 8
5.9 Two Marks Questions with Answers
5.10 University Questions with Answers (Long Answered Questions)

5.1 Busbar Protection

AU : Dec.-06,13, May-14,18

The busbar plays an important role in the supply system. The busbar faults are rare but if occurs there can be interruption of supply, considerable damage and loss. Hence busbar protection is must and it must be fast, stable and reliable. The busbar protection needs to protect not only the busbar but the apparatus associated with it such as circuit breakers, isolating switches, instrument transformers etc.

5.1.1 Busbar Faults

The various busbar faults can be classified as,

1. Failure of insulation due to material deterioration.
2. Failure of circuit breaker.
3. Earth fault due to failure of support insulator.
4. Flashover due to sustained excessive over voltages.
5. Errors in the operation and maintenance of switchgear.
6. Earthquake and mechanical damage.
7. Accidents due to foreign bodies falling across the busbars.
8. Flashover due to heavily polluted insulator.

5.1.2 Frame Leakage Protection of Busbar

All busbar protection schemes are mostly designed for earth faults. Each conductor is surrounded by the earthed metal barrier. All the metal frameworks are bonded together and insulated from earth. The switchgear framework is also insulated from lead cable sheaths.

The arrangement of frame leakage protection to a single busbar substation with a switchgear unit is shown in the Fig. 5.1.1. (See Fig. 5.1.1 on next page)

Metal supporting frame work known as fault bus is earthed through a CT. When the fault is there, a contact between conductor and earth results. This drives current through this CT. This energizes the frame leakage relay.

The CT energizing the check relay is mounted in neutral earth of the transformer. The contacts of check relay and frame leakage relay are in series.

Thus before tripping circuit gets energized both the relays must operate. Once both the relays operate due to earth fault, all the breakers will trip connecting the equipment to the busbar. Due to check relay, accidental operation of single relay to trip the circuit gets avoided.

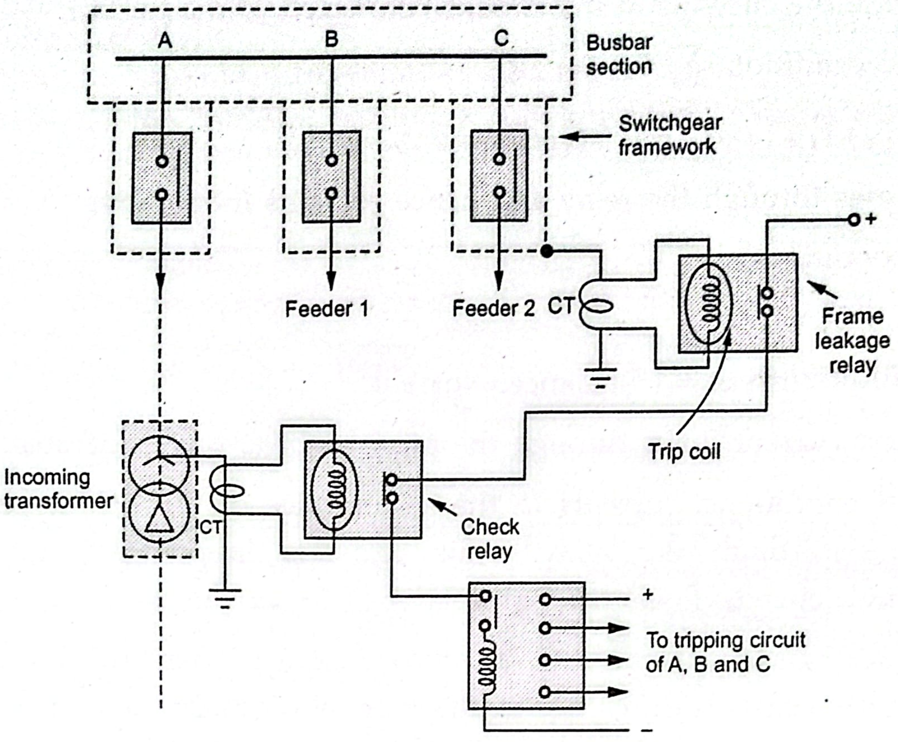

A
B
C
Busbar section
Switchgear framework
+
Feeder 1
Feeder 2
CT
Frame leakage relay
Trip coil
Incoming transformer
CT
Check relay
+
To tripping circuit of A, B and C
–

Fig. 5.1.1 Frame leakage protection of busbar

5.1.3 Circulating Current Protection of Busbar

This is nothing but the differential scheme of the protection of busbar. The circulating current principle states that under normal working conditions or external fault conditions, sum of the currents entering the bus equals sum of the currents leaving the bus. Under any abnormal conditions in the protected zone i.e. short circuit or phase to phase faults, the current condition gets disturbed and sensing this the relay can be operated.

The Fig. 5.1.2 shows the principle of circulating current protection of busbar.

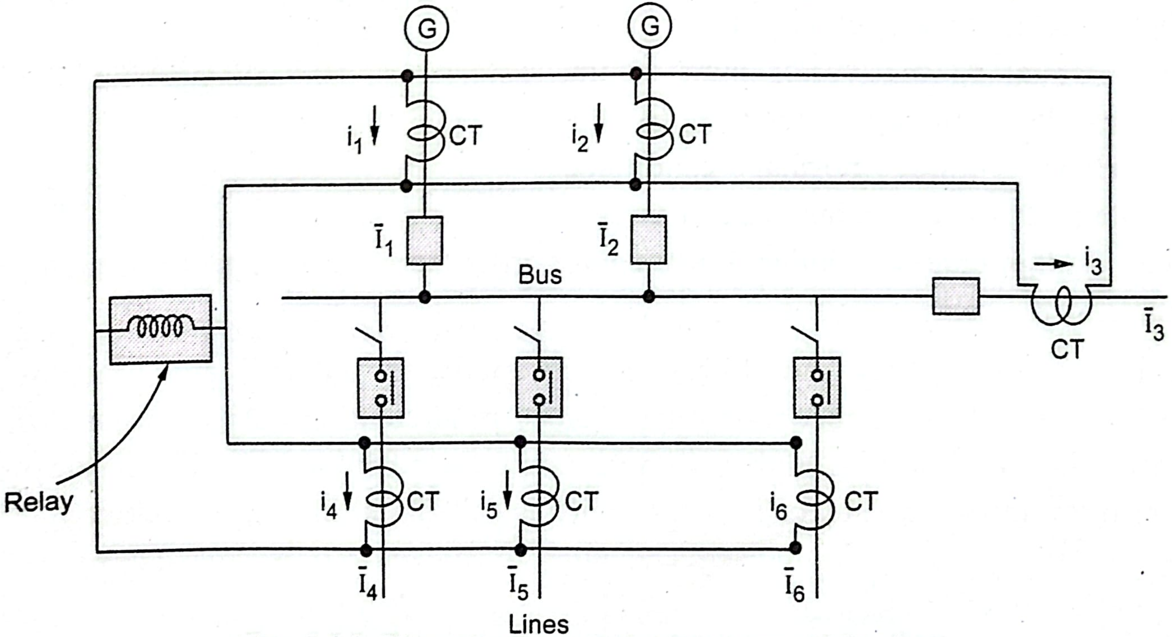

G
G
i_1
CT
i_2
CT
$\bar{I}_1$
$\bar{I}_2$
Bus
i_3
$\bar{I}_3$
CT
Relay
i_4
CT
i_5
CT
i_6
CT
$\bar{I}_4$
$\bar{I}_5$
$\bar{I}_6$
Lines

Fig. 5.1.2 Circulating current protection of busbar

$I_1, I_2 \ldots\ldots I_6$ are the currents in the circuits connected to the busbar.

Under normal condition, $\sum I = 0$.

i.e. $\bar{I}_1 + \bar{I}_2 + \bar{I}_3 + \bar{I}_4 + \bar{I}_5 + \bar{I}_6 = 0$ (vector sum)

No current flows through the relay and hence remains inoperative.

Under fault conditions,

$\bar{I}_1 + \bar{I}_2 + \bar{I}_3 + \ldots + \bar{I}_6 = \bar{I}_f$

where $\bar{I}_f$ = Fault current = Unbalanced current.

The unbalanced current flows through the relay and the relay operates.

Under normal conditions, currents in the secondaries of CT balance each other and no current flows through the relay. Thus relay is inoperative. Under any fault conditions, the fault current flows through relay coil to activate it.

To obtain exact balance of currents, all current transformers must have same ratio. But in practice there exists a difference in the magnetic conditions of iron cored current transformers and false operation of the relay is possible, at the time of external faults. For large fault currents there is a possibility of saturation of the cores of current transformers. To overcome such difficulties, a special type of C.T. having no iron core is used. It is called **linear coupler.**

The linear coupler has a property that its secondary voltage is proportional to the primary current and the secondary windings of all the linear couplers are connected in series to the relay. This is shown in the Fig. 5.1.3.

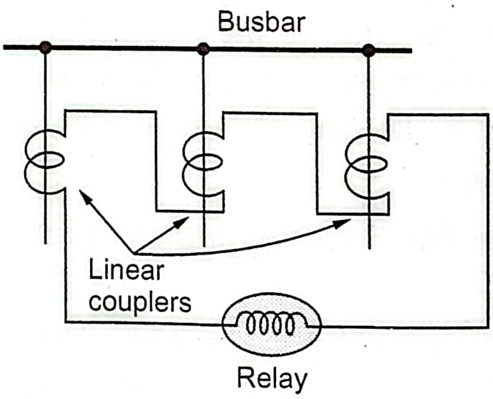


Fig. 5.1.3

The sum of the voltage outputs of linear couplers is equal to the vector sum of the voltages in the circuits connected to the busbars. Hence under normal conditions overall voltage in the secondary circuit is zero and relay is inoperative. Under fault conditions, there is resultant voltage in the secondary and the relay operates.

A high impedance relay can differentiate properly the internal and external faults compared to normal low impedance relay. Hence in circulating current protection, high impedance relays are used. A high resistance is connected in series with relay operating coil to get high impedance relay. This resistance is called **stabilising resistance.**

5.1.4 High Impedance Differential Protection of Busbar

Another method to provide differential protection to busbar is based on sensing a voltage drop across a high impedance, under fault conditions. The scheme is shown in the Fig. 5.1.4.

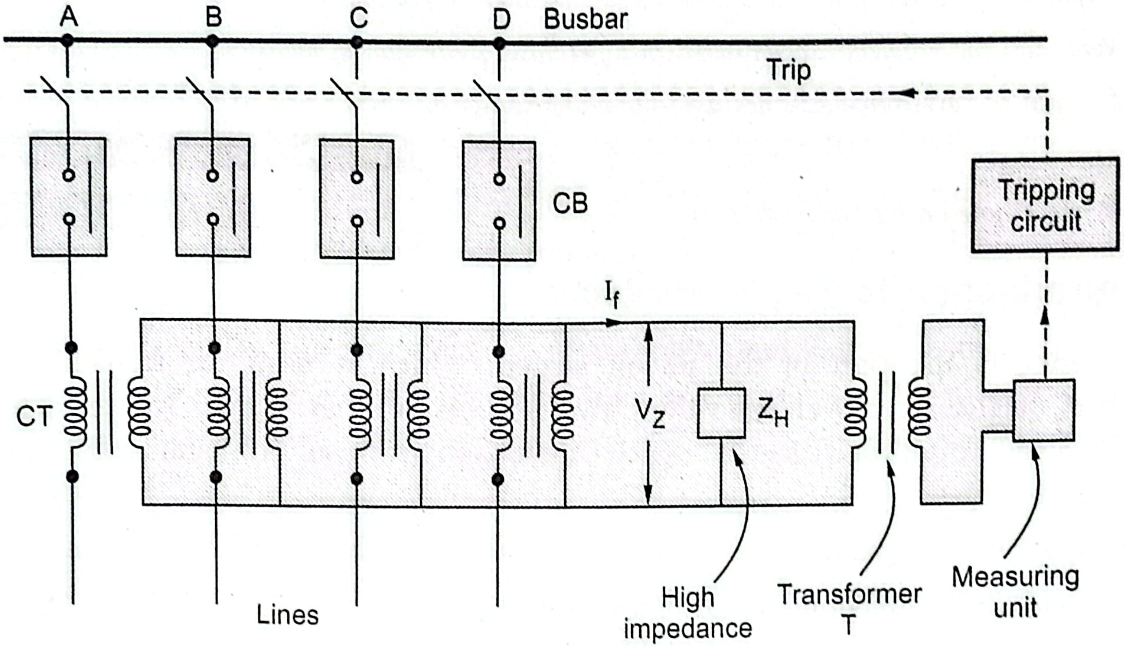


Fig. 5.1.4 High impedance busbar protection

The basic principle remains same as differential scheme. Under normal conditions vector sum of the currents in the lines is zero. Hence I_f i.e. current flowing through high impedance Z_H is zero. And the relay is inoperative.

During fault conditions, unbalanced current exists. Such an out of balance current I_f flows through Z_H causing a high voltage drop V_Z across it. It is given to a transformer. A measuring unit is connected to the secondary of this transformer which measures this drop and trips the relay accordingly. Main advantage is that as voltage drop is sensed, saturation of core of one of the current transformers has no effect on the protection scheme.

5.1.5 Difficulties in Busbar Protection

The various difficulties in the busbar protection are,

1. Current levels for different circuits are different.
2. Large number of circuits to be protected.
3. Saturation of cores of current transformers due to d.c. component in short circuit current is possible which produces ratio error.
4. Due to various bus sections, the scheme becomes complicated.
5. With large load changes, relay settings need to be changed.

Review Questions

1. *List the various possible busbar faults.*
2. *With neat figure, explain frame-leakage protection of bus-bar.*
3. *Explain differential protection of a bus having high impedance relay.*
4. *What are the problems encountered in differential protection of busbars ?*
5. *Explain the protective schemes used for protection of bus bar.*

AU : Dec.-06,13, May-18, Marks 8

6. *Write a note on busbar protection.* **AU : May-14, Marks 6**

5.2 Introduction to Feeder Protection

The feeder is the part of the power system which is used for transmission and distribution of electric power from the power station to other points. The term feeder is generally used in broad sense which includes overhead transmission lines and underground cables.

The protection of transmission lines is broadly classified as,

1) Overcurrent protection. 2) Distance protection.

3) Pilot protection.

The selection of the protection scheme depends on the following factors.

1) Economic aspects which ensures 100 % continuity of supply.

2) Type of feeders whether parallel, ring main etc.

3) Availability of pilot wires.

4) Number of switching stations in series between power station and receiving end.

5) Earthing of the system whether neutral is earthed or insulated.

Review Question

1. *What is feeder protection ? On which factors the selection of protection scheme for feeder depends ?*

5.3 Overcurrent Protection of Transmission Lines

The overcurrent protection is the simplest and cheapest method of providing protection to the transmission lines. The relays used in this method need readjustment whenever there is change in the system. The operating times of relays used in this method are large.

The overcurrent protection is further divided into following methods,

1. Nondirectional time and current graded method.
2. Directional time and current graded method.

5.4 Nondirectional Time and Current Graded Protection AU : May-11

The nondirectional time graded protection is mainly used for the radial feeders. The definite time relays are used in this method. These relays have instantaneous overcurrent relay followed by a timing relay. The contacts of the timing relay trip the circuit breaker.

The basic principle used in this method is that the minimum time of operation of the relays decreases from the generating power station to the remote substation. This is possible because of definite time relays in which accurate time setting independent of C.T. saturation can be achieved. This method is shown in the Fig. 5.4.1.

The Fig. 5.4.1 shows the overcurrent protection of a radial feeder. For a fault beyond D, the circuit breaker at D operates first with relay time of 0.3 sec. The protections at A, B and C operate as backup protection. For faults between C and D, the relay at C trips with a time delay step of 0.5 sec. The relay time at C is 0.8 sec. Thus for the section BC and AB, the time delay is successively increased. The time delay step generally lies between 0.3 to 0.5 sec.

The main disadvantage of this method is that the time of relay at power station increases to very high value if many sections are in series. If this time is more than 2 seconds then the protection is not recommended. Hence the tripping time for the faults near supply must be limited to 2 seconds.

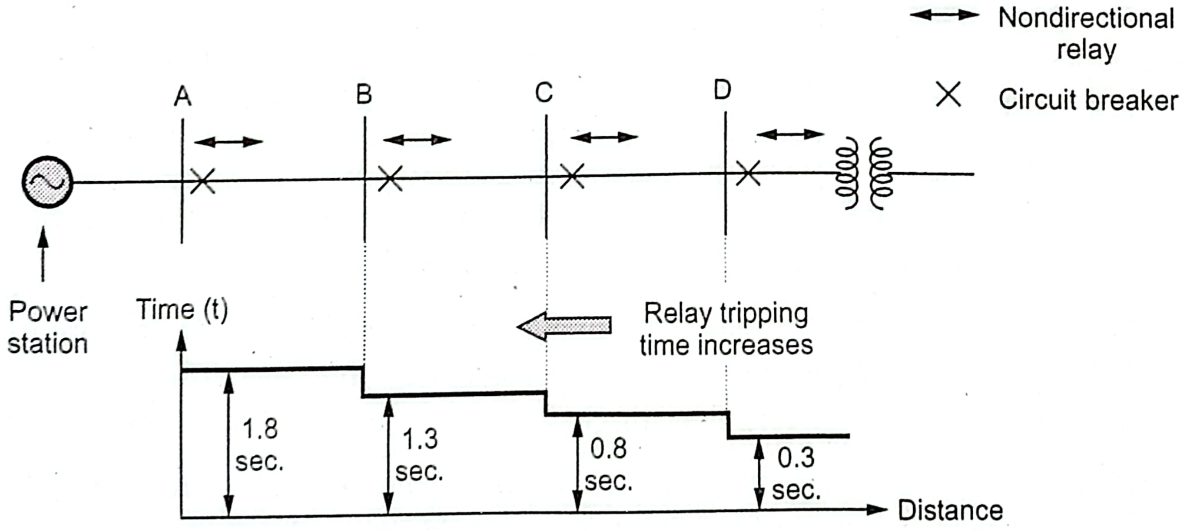


Fig. 5.4.1 Time grading for radial feeder

5.4.1 Use of Inverse Time Relays

This method is based on the principle that the short circuit current along the length of the protected transmission line decreases as the distance of the fault location increases from the power station. Thus the relays near the power station are set to trip at a progressively higher current. This is called **current grading protection**. The relays used are called high-set overcurrent relays.

The current graded can be applied to the system shown in the Fig. 5.4.1 with relays used as high-set overcurrent relays. Thus relay at A operates for the faults between A and B, the relay at B operates for the faults between B and C and so on. But this method has following limitations,

1. It is difficult for relay to differentiate the fault on either side of a certain section, as the difference in currents is small.
2. The magnitude of the fault current cannot be obtained accurately.
3. The accuracy of the relays differ in transient conditions.

Hence instead of using current grading alone, Inverse Definite Minimum Time (IDMT), relays are added in the relay system. Thus the scheme becomes the combination of current and time graded protection. For differentiating the operation, the relays are set to protect only part of the feeder, generally 80 % of the feeder.

The characteristics of such combined high-set overcurrent instantaneous relay and IDMT relays are shown in the Fig. 5.4.2.

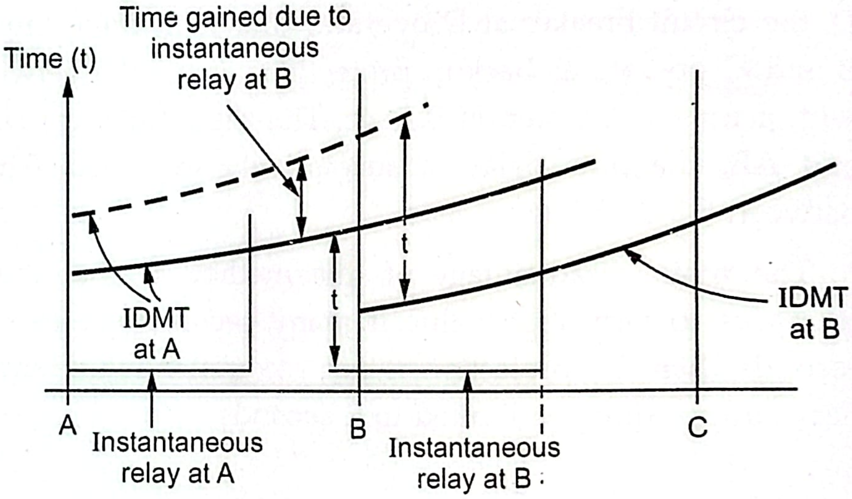


Fig. 5.4.2 Combination of instantaneous and IDMT relays

For proper differentiation of operation, the instantaneous relays are set so that they do not operate for the faults beyond the protected feeder.

The instantaneous element should be set for more than 150 % of maximum fault current at the end of the line section which is protected by the relay. This care takes into account the effect of transients and over-reach.

Over-reach is a tendency of relay to pickup for the faults, which are located further away from the point, expected to be protected by the relay, neglecting the d.c. component of fault current. The d.c. component of fault current wave produces the transient over-reach. The portion of feeder to be protected depends on the % over-reach of the relay used. The % over-reach of relay is given by,

$$\% \text{ Over-reach} = \frac{A-B}{A} \times 100$$

Where, A = Relay pick up current in steady state r.m.s. value.

B = The steady state r.m.s. current which when fully offset causes the relay pick up.

5.4.2 Setting of Inverse Overcurrent Relays

The relays are so selected that,

1. They operate for short circuits in their own section
2. Provide backup protection for faults in next section

The operating time of relay is graded as,

$$T_A = T_B + CB_2 + O_A + F$$

Where, T_A = Operating time of relay at A

T_B = Operating time of relay at B

CB_2 = Operating time of circuit breaker at B

O_A = Overtravel time of relay at A

F = Factor of safety

The **overtravel** is the operation of relay moving elements due to inertia, though actuating force is removed. The overtravel of 0.1 sec. is generally assumed for inverse time relays.

The Time Multiplier Setting (TMS) is another setting required for inverse time relays. It is given by,

$$\text{TMS} = \frac{T}{T_m}$$

Where, T = Required time of operation

T_m = Time obtained from the relay characteristics curve at TMS = 1.0 and using PSM equivalent to maximum fault current

The relay characteristic curve called IDMT curve for TMS = 1.0 is the curve of Plug Setting Multiplier (PSM) against the time.

$$\text{PSM} = \frac{\text{Primary current}}{\text{Relay current setting} \times \text{C.T. ratio}} = \frac{\text{Primary current}}{\text{Primary operating current}}$$

Thus if maximum fault current is 4000 A and relay operating current is 400 A then PSM = 4000/400 = 10. Then for PSM = 10, read the time from relay characteristics for TMS = 1.0 which is T_m and using this T_m, obtain TMS.

5.4.3 Disadvantages of Nondirectional Time and Current Graded Method

The various disadvantages of nondirectional time and current graded method are,

1. The time lag is not desirable for short circuit faults, which is provided in this method.
2. For new connections, the co-ordination of relays is difficult and require changes, in settings.
3. For long transmission lines, the method is not suitable as very rapid fault clearing is necessary in long transmission line systems.
4. Not suitable for ring mains or interconnected systems.

Review Questions

1. *What is meant by time graded over current protection ?*
2. *Explain with neat diagram the time graded protection of feeders.*
3. *What is over-reach ? How it is calculated ?*
4. *How setting of inverse overcurrent relays is achieved ?*
5. *What are the disadvantages of nondirectional time and current graded methods ?*
6. *How the various grading systems are used for the discrimination between the faults in overcurrent protection ?* **AU : May-11, Marks 8**

5.5 Directional Time and Current Graded Protection

AU : May-06,13

In many case, it is necessary to obtain the information about direction of flow of power where power can flow to the fault from both the directions. In such cases, it is necessary that the circuit breakers on both sides must trip. Thus the directional relays are necessary for such systems. The examples of such systems are parallel feeders, Tee feeders, ring mains and interconnected system. The protection of such systems is obtained using both directional as well as nondirectional relays.

5.5.1 Parallel Feeder Protection

The Fig. 5.5.1 shows the parallel connection of three feeders which are connected between a power station and remote supply point.

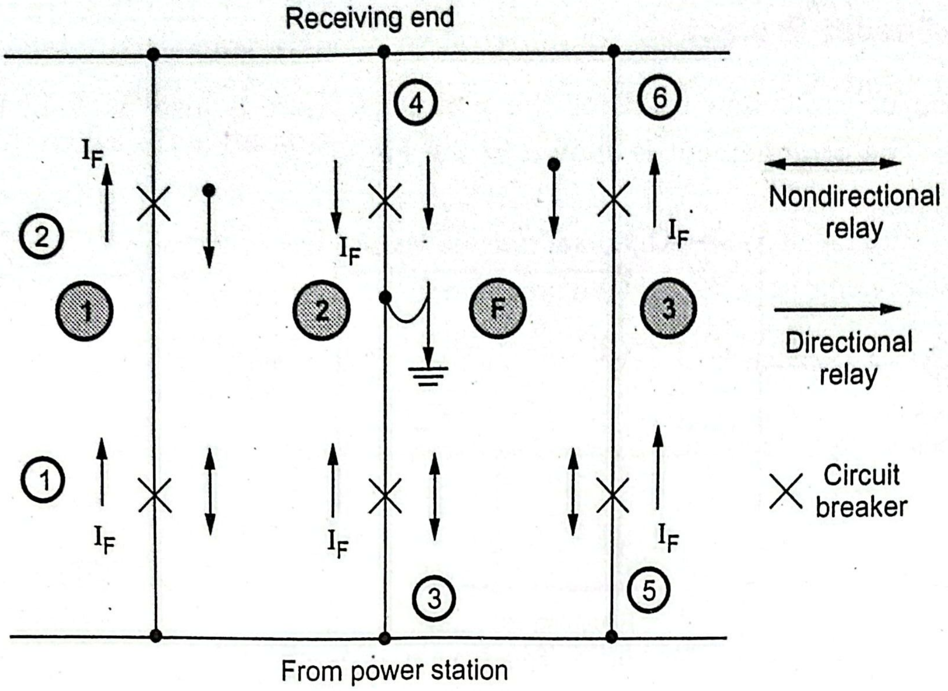


Fig. 5.5.1 Parallel feeder protection

Let the fault occurs on the second feeder. This fault is supplied from three paths,

1) From power station directly.
2) From feeder 1 through receiving end busbar indirectly.
3) From feeder 3 through receiving end busbar indirectly.

It is necessary to open, circuit breakers 3 and 4, to clear this fault and disconnect the faulty feeder. Thus the nondirectional relays are employed on supply side while the directional relays are employed on receiving end. The directional relays on receiving end operate only when the fault power is feeding in the direction of the arrow.

Hence when fault F on feeder 2 occurs, then all three nondirectional relays on supply side will operate while only directional relay 4 will operate on receiving end. But it is important that circuit breakers on feeder 1 and 3 on supply side should not operate. This is achieved in practice by keeping the time of operation of relays 1 and 5 more than the time of operation of relay 3. The fault current in feeders 1 and 3 is much smaller than the fault current in feeder 2 as 1 and 3 provide high impedance as fault gets supplied indirectly. The relays have inverse time characteristics hence for small current, the relays take long time to operate. Thus by the time relay 3 operates and isolate the fault, the relays 1 and 5 do not operate. Once fault gets cleared, the relays 1 and 5 remain operative and feeders 1 and 3 keep on supplying the power. This is **time graded overcurrent protection of parallel feeders.**

5.5.2 Tee Feeder Protection

The method of protection used for the parallel feeders is also used in the protection of tee feeders. The arrangement is shown in the Fig. 5.5.2.

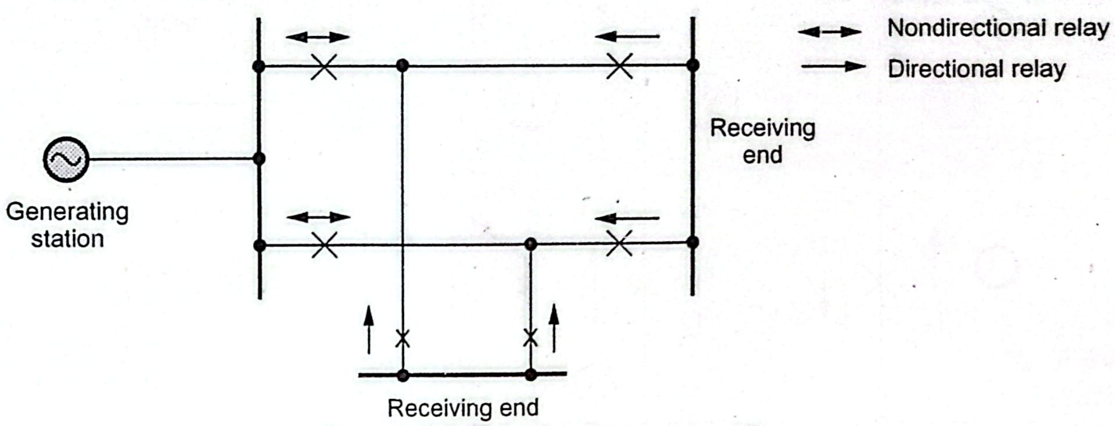

Circuit breaker
Nondirectional relay
Directional relay
Receiving end
Generating station
Receiving end

Fig. 5.5.2 Tee feeder protection

In this method also, the arrangement is such that the relay elements near the generating station are nondirectional while those near the receiving ends are directional. The directional relays are set for the lower time setting as well as current setting than the nondirectional relays. Thus the directional relays operate before the nondirectional.

5.5.3 Ring Main and Interconnected Systems

In ring main system, the various substations are interconnected by the alternate routes and hence the overall system form a closed path. This ensures the continuity of the supply to the healthy part if any section of the ring is damaged and separated for the repairs.

The Fig. 5.5.3 shows the method of protection used for the ring systems using nondirectional as well as directional relays.

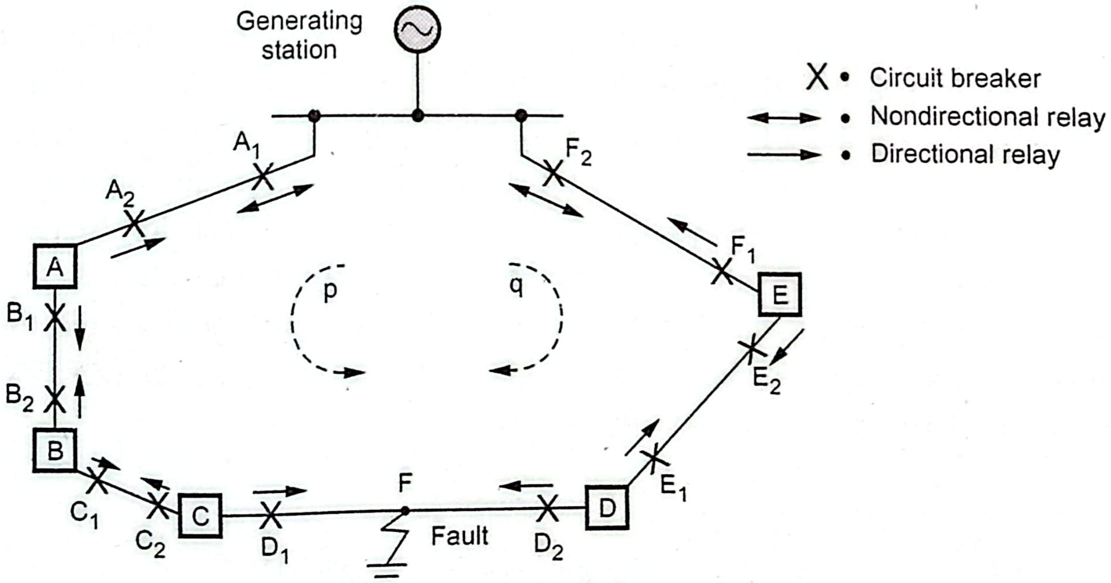

Generating station
Circuit breaker
Nondirectional relay
Directional relay
A1
A2
F2
F1
A
E
B1
B2
p
q
E2
B
E1
C1
C2
C
F
D
D1
Fault
D2

Fig. 5.5.3 Protection of ring main system

The relays near generating stations must be nondirectional while the other relays are directional. The current and time settings of directional relays are lower than the nondirectional relays. The outgoing directional relays are set with the decreasing time limits.

If the fault develops in a particular section say CD, then it will be fed from the source through path 'p' and path 'q' as shown in the Fig. 5.5.3. In such case, the settings are such that the relays at D_1 and D_2 only will trip and disconnect the faulty section. The remaining relays are inoperative.

When an interconnector is used in such system, the relays used on it must be of nondirectional type.

Review Questions

1. *Explain parallel feeder protection.*
2. *Explain tee feeder protection.*
3. *Explain ring main system protection.*
4. *Discuss the time graded overcurrent protection for parallel feeders.* **AU : May-06,13, Marks 6**

5.6 Differential Protection of Feeders (Pilot Wire Protection)

AU : May-06,08,11,15,22, Dec.-11

In differential protection scheme, the current entering at one end of the line and leaving from other end of the line is compared. The **pilot wires** are used to connect the relays. Under normal working condition, the two currents at both ends are equal and pilot wires do not carry any current, keeping relays inoperative. Under fault conditions, the two currents at two ends are no longer same, this causes circulating current to flow through pilot wires. This causes relays to trip which operate the circuit breakers to isolate the faulty section.

The various schemes used with this method of protection are,

1. Merz-Price voltage balance system 2. Translay scheme

5.6.1 Merz-Price Voltage Balance System

The Fig. 5.6.1 shows Merz-Price voltage balance system used for the three phase feeders. (See Fig. 5.6.1 on next page)

Under normal condition, current entering the line at one end is equal to the current leaving from the other end.

Thus equal and opposite voltages are induced in the secondaries of C.T.s. at the two ends. Hence no current flows through relays.

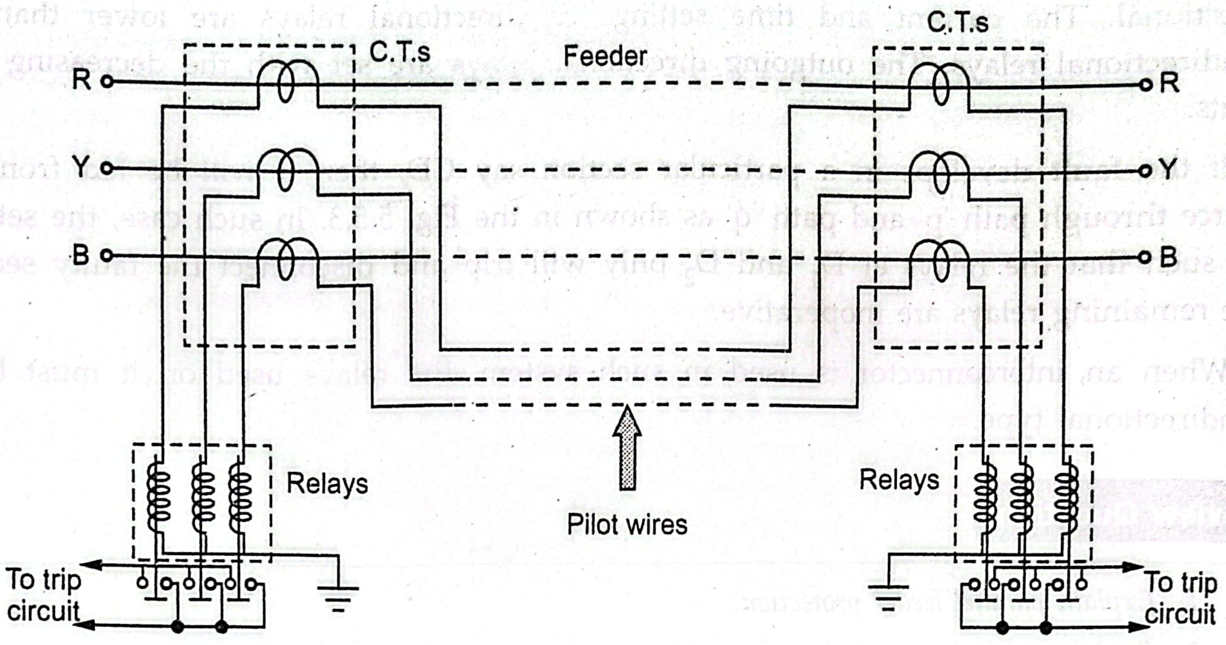


Fig. 5.6.1 Merz-price protection for feeder

Under fault condition, two currents at the two ends are different. Thus the secondary voltages of the two C.T.s also differ. This circulates a circulating current through the pilot wires and the relays. Thus the relays trip the circuit breakers to isolate the faulty section.

The **advantages** of this method are,

1. Can be used for parallel as well as ring main system.
2. Provides instantaneous protection to the ground faults.

The **limitations** of this method are,

1. The C.T.s used must match accurately.
2. The pilot wires must be healthy without discontinuity.
3. Economically not suitable as the cost is high due to long pilot wires.
4. Due to long pilot wires, capacitive effects may affect the operation of the relays.

5.6.2 Translay Scheme

The translay relay is another type of differential relay. The arrangement is similar to overcurrent relay but the secondary winding is not closed on itself. Additionally copper ring or copper shading bands are provided on the central limb as shown in the Fig. 5.6.2.

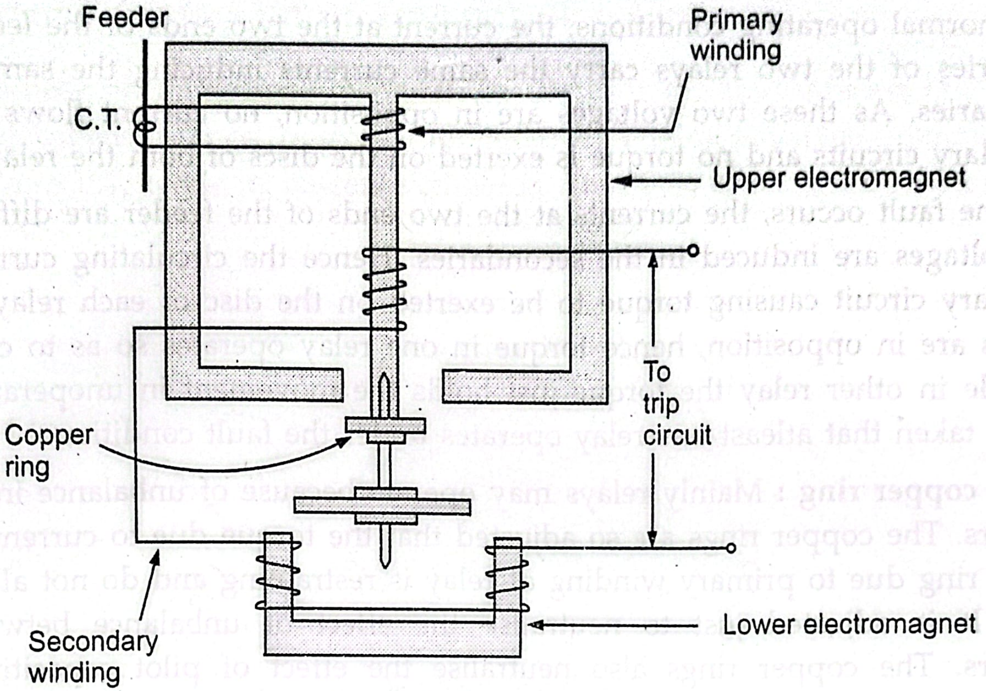

Feeder
Primary winding
C.T.
Upper electromagnet
To trip circuit
Copper ring
Secondary winding
Lower electromagnet

Fig. 5.6.2 Translay relay

These type of relays are used in the feeder protection and the scheme is called Translay scheme. In this scheme, two such relays are employed at the two ends of feeder as shown in the Fig. 5.6.3.

The secondaries of the two relays are connected to each other using pilot wires. The connection is such that the voltages induced in the two secondaries oppose each other. The copper coils are used to compensate the effect of pilot wire capacitance currents and unbalance between two current transformers.

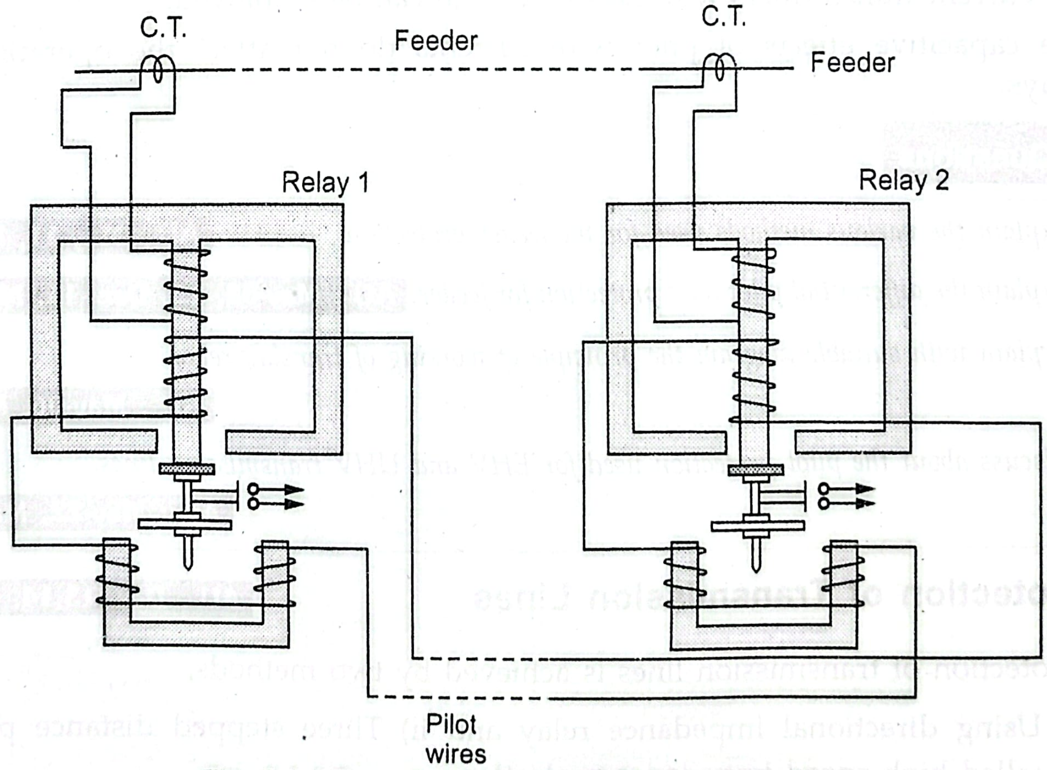

C.T.
Feeder
C.T.
Feeder
Relay 1
Relay 2
Pilot wires

Fig. 5.6.3 Translay scheme of feeder protection

Under normal operating conditions, the current at the two ends of the feeder is same. The primaries of the two relays carry the same currents inducing the same voltage in the secondaries. As these two voltages are in opposition, no current flows through the two secondary circuits and no torque is exerted on the discs of both the relays.

When the fault occurs, the currents at the two ends of the feeder are different. Hence unequal voltages are induced in the secondaries. Hence the circulating current flows in the secondary circuit causing torque to be exerted on the disc of each relay. But as the secondaries are in opposition, hence torque in one relay operates so as to close the trip circuit while in other relay the torque just holds the movement in unoperated position. The care is taken that atleast one relay operates under the fault condition.

Role of copper ring : Mainly relays may operate because of unbalance in the current transformers. The copper rings are so adjusted that the torque due to current induced in the copper ring due to primary winding of relay is restraining and do not allow the disc to rotate. It is adjusted just to neutralise the effect of unbalance between current transformers. The copper rings also neutralise the effect of pilot capacitive currents. Though the feeder current is same at two ends, the pilot capcitive currents may flow in the pilots. This current leads the secondary voltage by 90°. The copper rings are adjusted such that no torque is exerted on the disc, due to such capacitive pilot currents, by adjusting the angle between the induced current in the disc and secondary current to be 90 °.

The **advantages** of this scheme are,

1. Only two pilot wires are required.
2. The cost is very low.
3. The current transformers with normal design can be employed.
4. The capacitive effects of pilot wire currents do not affect the operation of the relays.

Review Questions

1. *Explain the various methods used for the feeder protection.* **AU : May-11, Marks 8**
2. *Explain the differential pilot wire protection for feeder.* **AU : May-08, 15, Dec.-11, Marks 16**
3. *Explain with suitable diagram the principle of working of translay relay.* **AU : May-06, Marks 8**
4. *Discuss about the pilot protection used for EHV and UHV transmission lines.* **AU : May-22, Marks 13**

5.7 Protection of Transmission Lines

AU : Dec.-13,14, May-19

The protection of transmission lines is achieved by two methods,

i) Using directional impedance relay and ii) Three stepped distance protection called high speed impedance protection.

5.7.1 Distance Protection of Transmission Lines

Let us see how an impedance relay can be used for the transmission line protection. The scheme is called distance protection for the transmission line. The voltage coil of the relay is fed from P.T. while its current coil is fed from C.T. as shown in the Fig. 5.7.1.

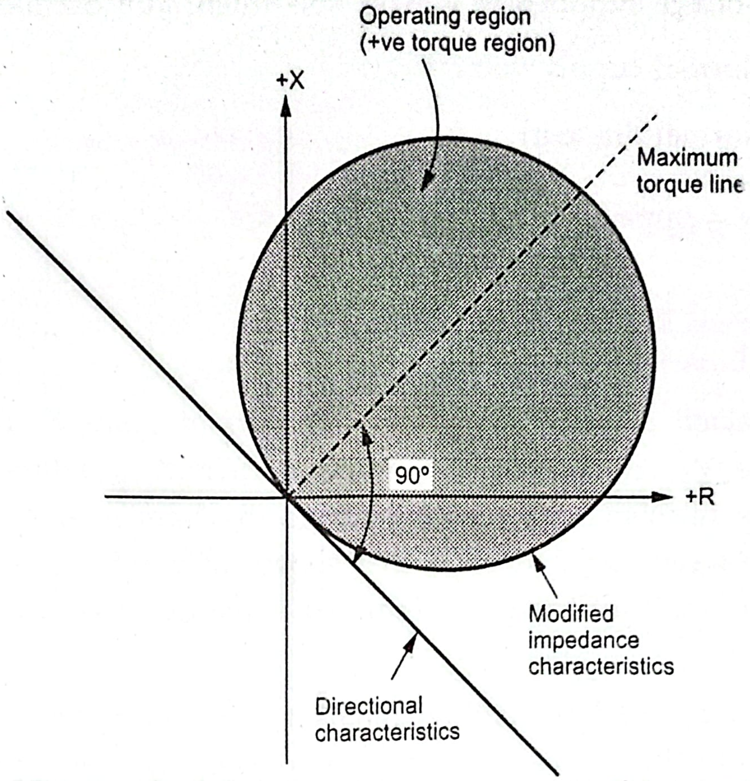

Operating region
(+ve torque region)
+X
Maximum torque line
90°
+R
Modified impedance characteristics
Directional characteristics

Fig. 5.7.1 Modified directional impedance relay characteristics

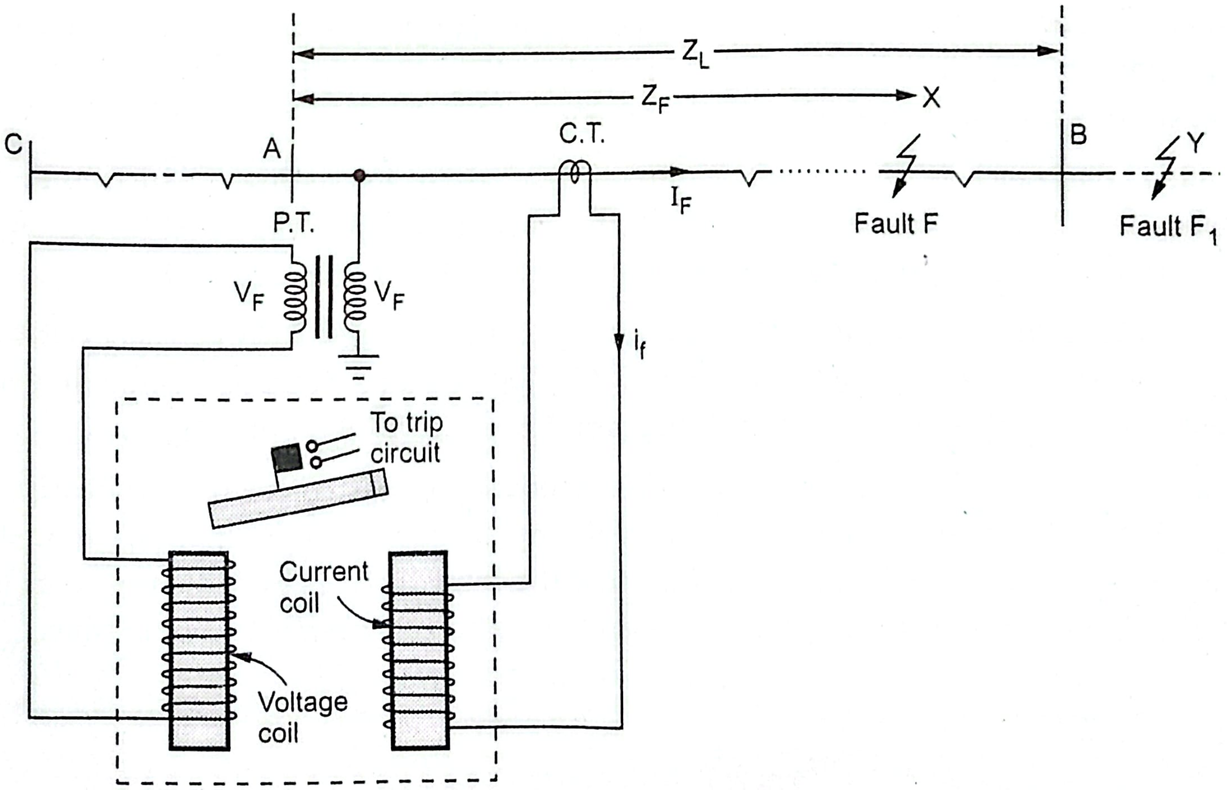

Z_L
Z_F
X
C
A
C.T.
B
Y
I_F
Fault F
Fault F_1
P.T.
V_F
V_F
i_f
To trip circuit
Current coil
Voltage coil

Fig. 5.7.2 Use of impedance relay

Let I_F = Line current when fault occurs at point X

V_F = Supply voltage when fault occurs at point X

i_F = Current supplied to current coil when fault occurs

V_F = Voltage supplied to voltage coil when fault occurs

V = Normal supply voltage

I = Normal line current

$$Z_L = \frac{V}{I} = \text{Impedance of healthy section}$$

$$Z_F = \frac{V_F}{I_F} = \text{Impedance when fault occurs}$$

The relay is connected at point A. The fault occurs at point X. The voltage coil of relay receives voltage V_F and current coil receives current i_F, when fault occurs. The setting of the relay is selected such that it protects the transmission line upto point B. Thus for any fault between A-B similar to that shown at point X, the impedance under fault condition will be less than the predetermined value of impedance Z_L and the relay will operate.

If the impedance relay used is nondirectional, it can protect the line from faults for all fault positions within the section AC too. So nondirectional relay provides protection on either side of the point where relay is located. But if the portion of line AB only is to be protected, then the directional impedance relay can be used. As directional unit permits tripping only in one direction, the section AB will be protected but relay will not operate for any fault positions between section AC.

Whether the relay is directional or nondirectional, if its setting is such that for impedance less than Z_L defined upto point B, the relay should operate then for any fault positions to the right of point B like point Y the relay will not operate.

The characteristics of the directional distance scheme discussed above can be shown on R-X diagram. It is shown in the Fig. 5.7.3. The various sections of the line are represented by straight lines on the R-X diagram. (See Fig. 5.7.3 on next page)

For fault at X, $Z_f < Z_L$ hence point X is in the operating region and relay will trip. So for any fault position along line AB, relay will trip as the entire section AB is in the protected zone. For fault at Y, it can be seen that the impedance $Z_f > Z_L$ hence point lies outside the circle hence in the negative torque region and relay remains inoperative.

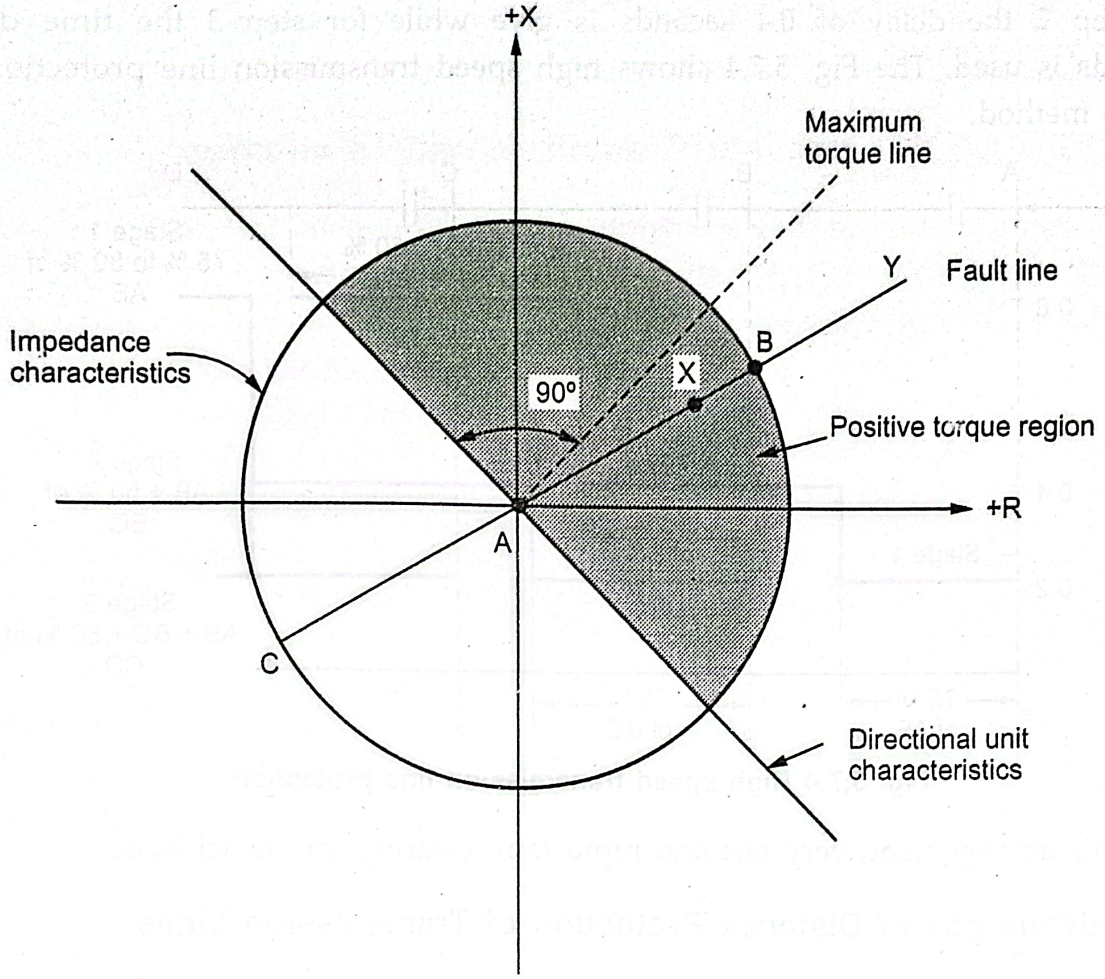

+X
Maximum torque line
Y
Fault line
B
X
Impedance characteristics
90°
Positive torque region
+R
A
C
Directional unit characteristics

Fig. 5.7.3

5.7.2 Three Stepped Distance Protection of Transmission Lines

Practically in some cases it is necessary to operate the relay very fast, in about 20 ms, to rapidly disconnect the faults. Such relays are called high speed distance relays.

The high speed protection of transmission line uses the combination of :

1) Definite impedance relay elements used to operate instantaneously when fault occurs within the nearest 75 % or more of the section controlled.

2) A short definite time lag is introduced to cover the faults in the remaining sections and for the backup protection on the following section.

This protection practically uses three steps using three definite impedance elements on each phase.

Step 1 : It is set so as to operate within first 75 % to 80 % of the transmission line section.

Step 2 : It is set to operate for remaining 25 % and 50 % of the next line section.

Step 3 : It is set to operate for faults beyond the 50 % of the next line section.

For step 2 the delay of 0.4 seconds is give while for step 3 the time delay of 0.8 seconds is used. The Fig. 5.7.4 shows high speed transmission line protection using three step method.

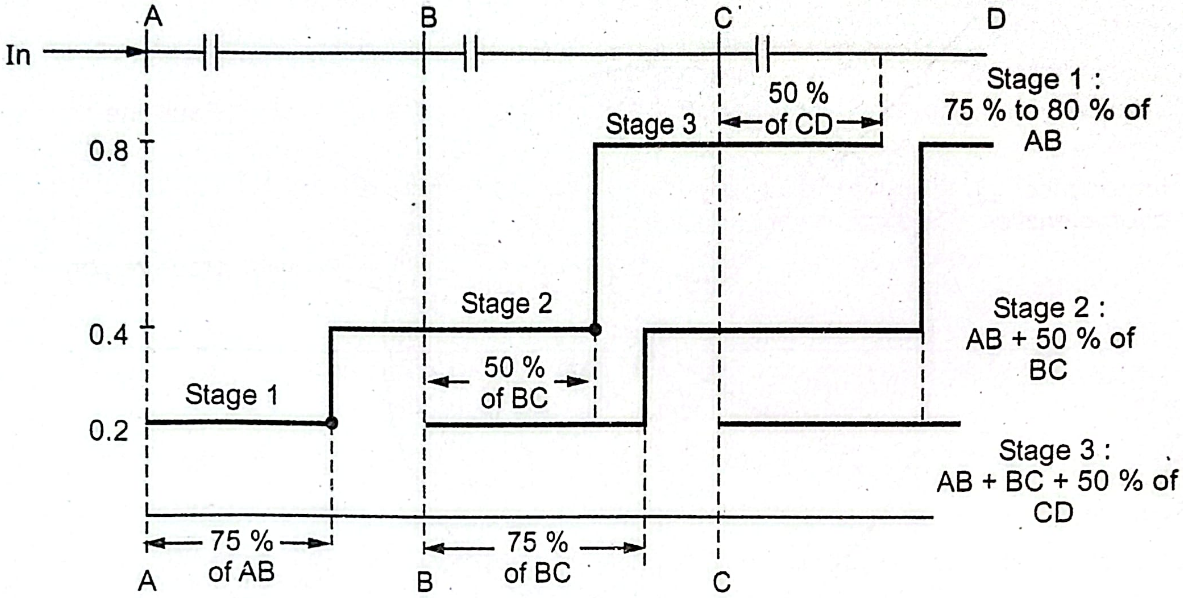

A
B
C
D
In
0.8
0.4
0.2
Stage 1
Stage 2
Stage 3
50 % of CD
50 % of BC
Stage 1 : 75 % to 80 % of AB
Stage 2 : AB + 50 % of BC
Stage 3 : AB + BC + 50 % of CD
75 % of AB
75 % of BC
A
B
C

Fig. 5.7.4 High speed transmission line protection

With this arrangement, very fast and rapid fault clearing can be achieved.

5.7.3 Advantages of Distance Protection of Transmission Lines

The distance relay protection is preferred for the protection of transmission lines compared to overcurrent protection because of the following advantages.

1. The distance protection is very fast without time lag. The overcurrrent protection is slow with time lag.
2. For long transmission lines, high speed fault clearing is necessary, which is provided by distance protection. It is not possible with overcurrent protection.
3. The operation of distance protection is independent of changes in the magnitude of the short circuit current.
4. The operation of distance protection is not very much affected by the generation capacity.
5. The overcurrent protection is not suitable for ring main or interconnected systems.

Review Questions

1. *With neat sketches explain the different types of protective schemes for transmission lines.* **AU : Dec.-13, May-19, Marks 16**
2. *Explain three stepped distance protection of transmission lines.* **AU : Dec.-14, Marks 8**
3. *Explain the use of an impedance relay for the protection of transmission lines.*

4. *Explain in what way distance protection is superior to over current protection for the protection of transmission lines.* **AU : Dec.-14, Marks 6**

5.8 Block Schematic of Carrier Aided Protection **AU : May-15, Dec.-15**

Carrier aided protection is used for the protection of transmission lines. The carrier currents with high frequency range are transmitted and received with the help of transmission lines for protection. The schematic representation of carrier current protection is shown in the Fig. 5.8.1.

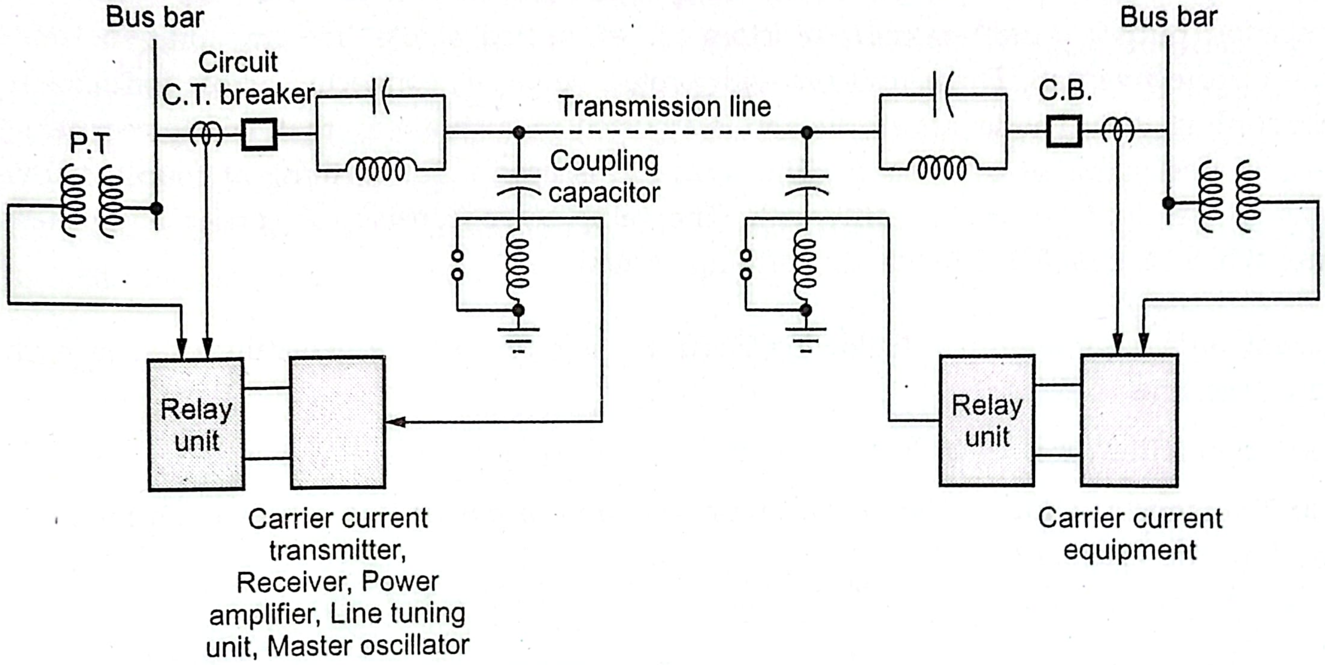

Bus bar
Circuit
C.T. breaker
P.T
Transmission line
Coupling
capacitor
Bus bar
C.B.
Relay unit
Relay unit
Carrier current transmitter, Receiver, Power amplifier, Line tuning unit, Master oscillator
Carrier current equipment

Fig. 5.8.1 Schematic of carrier current protection

The identical carrier equipments which include transmitter, receiver, line tuning unit, master oscillator, power amplifier etc. are provided at each end of the transmission line. The description of various blocks in the schematic representation is given below.

1. Coupling capacitor : The various carrier equipments described above are connected to the transmission line with the help of coupling capacitor. The capacitive reactance is given by $\frac{1}{\omega C}$. Hence for carrier frequency it offers less reactance while high reactance for normal power frequency. It can be seen that the carrier current signals are allowed to pass through this capacitor and enter in carrier equipment while power frequency currents are blocked. The inductance connected in series with the coupling capacitor reduces the impedance to further low value. Thus a condition of resonance is achieved at carrier frequency.

2. Line Trap Unit : This unit is between the busbar and the connection of coupling capacitor to the line. It consists of parallel combination of inductance (L) and capacitance (C) acting as tuned circuit. This circuit offers low impedance to power frequency currents while offers very high impedance to carrier frequency currents which prevents the high frequency carrier to enter in the neighbouring line and carrier currents flow only in the protected line.

3. Protection and Earthing of Coupling Equipment : Due to lightning, switching transients or faults, overvoltage surges are produced on the transmission lines. These overvoltages may produce stress on coupling equipment and line trap unit. For protection purpose, the nonlinear resistors are connected across line trap unit in series with a protective gap. These resistors with protective gap is connected across inductor in the coupling unit. The length of the gap is adjusted in such a way that, spark over takes place at a set value of overvoltage. The earth rod is used is for earthing of coupling unit so as to get low resistance earth path. The relay room consists of carrier equipment panel which is connected to station earthing system.

4. Electronic Equipments : Following electronic equipments are generally used at each end of the line,

a) Transmitter unit   b) Receiver unit   c) Relay unit

a) Transmitter Unit : The general representation of power line carrier equipments is shown in the Fig. 5.8.2.

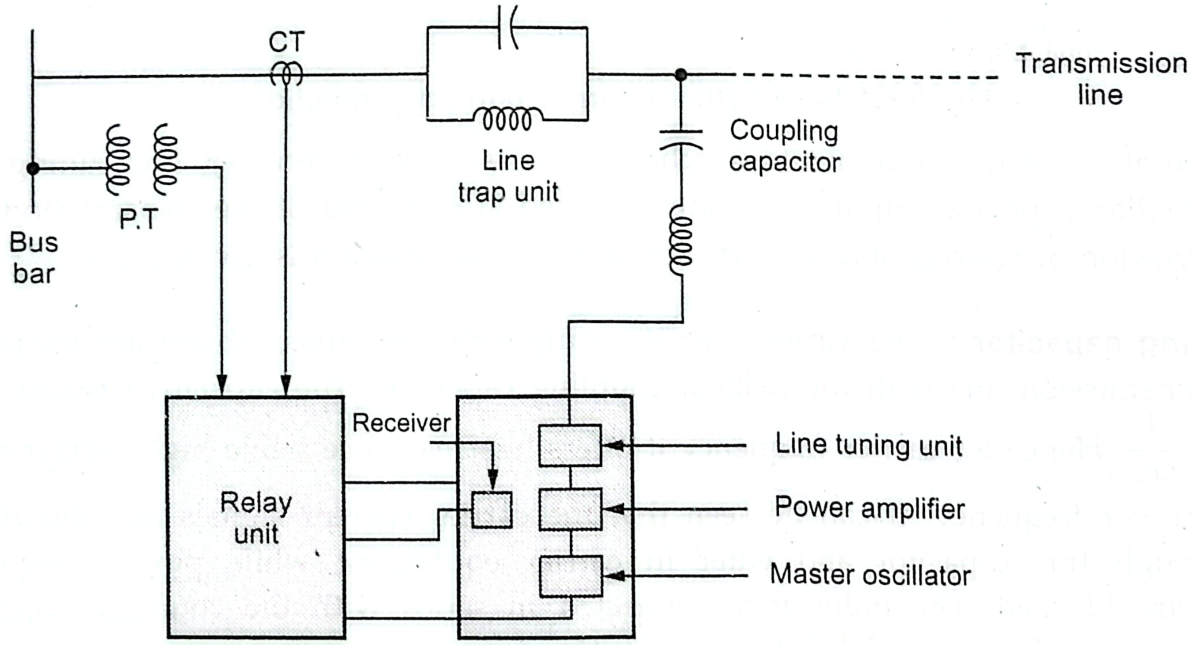


Fig. 5.8.2 Representation of carrier current protection unit

Normally the frequencies with range from 50 to 500 kHz are employed in various frequency bands with each has specific bandwidth. The oscillator is used for the generation of carrier frequency and it is tuned for a particular frequency which is chosen for particular application. Sometimes a crystal oscillator may also be used which gives particular bandwidth after selecting particular type of crystal. Voltage stabilizers are employed for maintaining the oscillator output voltage constant. The losses in the transmission path between transmitter and receiver at remote end of line are overcome with the help of amplifier which increases the level of the signal to be transmitted.

The attenuation in signal is due to losses in coupling equipment which are constant for given frequency range. Depending on length of line, frequency whether conditions and the size and type of line, the line losses vary.

If weather is fairly reasonable then the attenuation is of the order of 0.1 dB/kHz at 80 kHz which increases 0.2 dB/km at 380 kHz. If we consider 250 km line then the output of power amplifier is about 20 W. For a particular bandwidth the amplifier should give maximum power. Depending on the type of protection required, various methods are adopted for the control of transmitter. The interconnection between oscillator and amplifier is done through control circuit. The block diagram representation of transmitting unit is shown in the Fig. 5.8.3 (a).

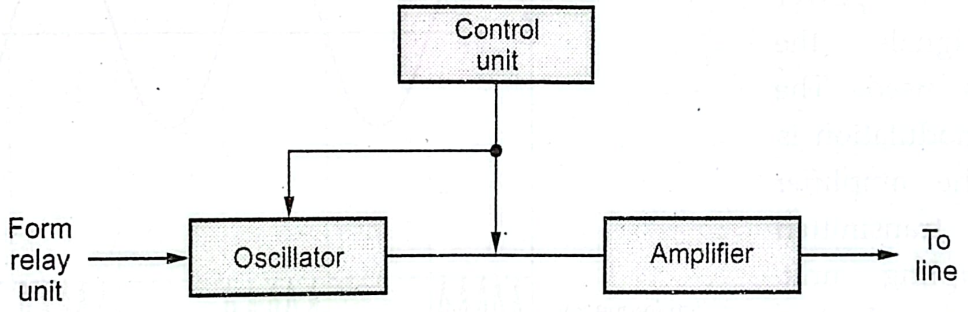

Control unit
Form relay unit
Oscillator
Amplifier
To line

Fig. 5.8.3 (a) Transmitting unit

b) Receiving Unit : The block schematic of receiving unit is shown in the Fig. 5.8.3 (b).

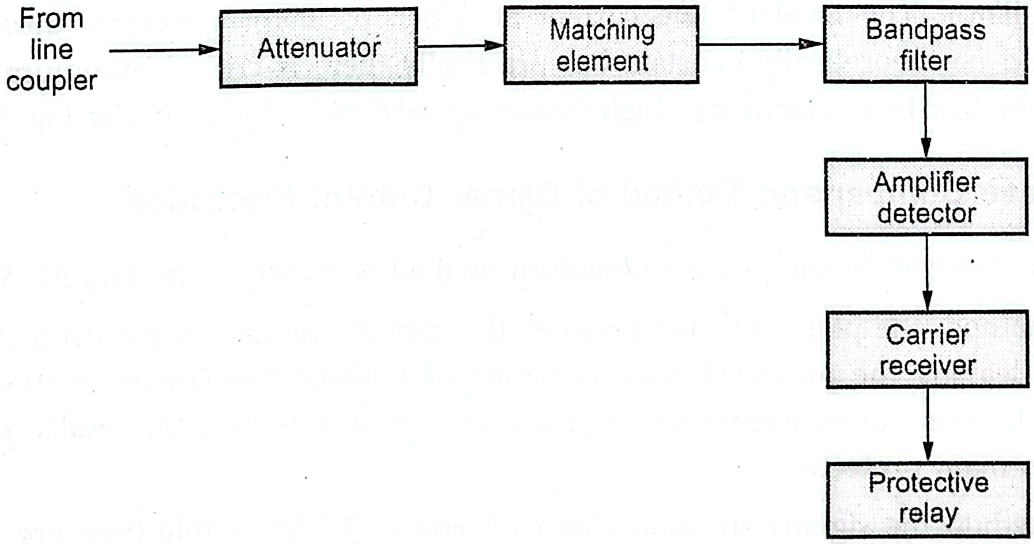

From line coupler
Attenuator
Matching element
Bandpass filter
Amplifier detector
Carrier receiver
Protective relay

Fig. 5.8.3 (b) Receiving unit

The signal is reduced to a safe value with the help of attenuator. The undesired signals which are signals from subsequent sections or spurious signals are prevented by using band pass filter. The matching element matches the impedance of the transmission line and receiving section. The undesired signals are generated either by short circuits or radio interferences. The malfunctioning of this unit is avoided due to the noise signals by using the set value above 2 milliwatts which is above noise level. If the carrier signals have power level of 20 W and receiver unit is set at higher level of 5 milliwatts then the operation is unaffected by spurious signals. For avoiding the overloading, the signals should be attenuated before applying it to the amplifier detector.

c) Frequency Spacing : The subsequent line sections use various frequencies. The carrier signals are prevented from entering into next section by wave traps. The filters from receiving unit filters other frequencies. The frequency bands of various sections are properly co-ordinated.

d) High Frequency Signal Modulation : For modulation of power frequency signals, the modulator is used. The signal after modulation is passed to the amplifier and then transmitted through coupling unit. From the half cycle line currents, the required blocks of carrier signals are generated with the help of oscillator. The level of line current at which oscillator generates these carrier blocks should be theoretically constant but practically there is critical minimum current. The modulation of line current into high frequency carriers is shown in the Fig. 5.8.4.

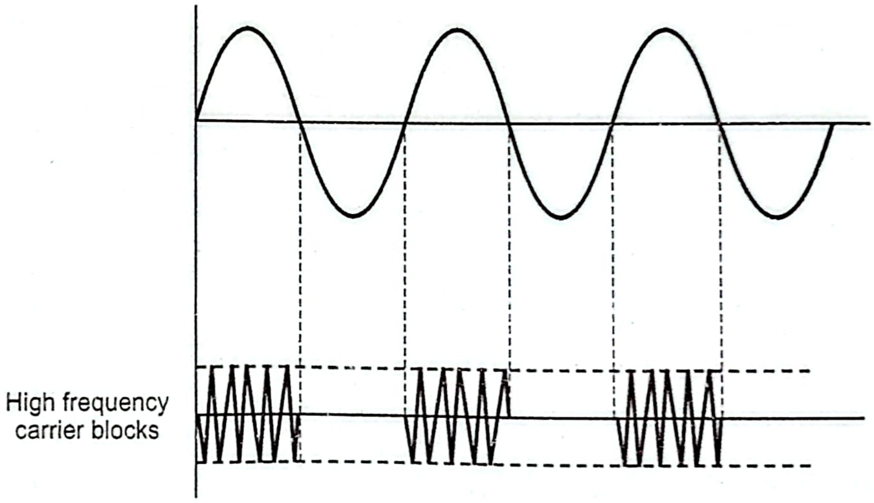


Fig. 5.8.4 Modulation of line current

5.8.1 Phase Comparison Method of Carrier Current Protection

The block diagram of the phase comparison method is shown in the Fig. 5.8.5.

In this method, the phase relation between the current entering in the protected zone and current leaving the protected zone is compared without comparison of magnitudes of currents. It does not provide backup protection which is to be additionally provided but it acts as main protection.

In this method the signals are sent from each end of the line while they are received at the other end. The signals are obtained from C.T. secondaries and are related to the current flow in the main line.

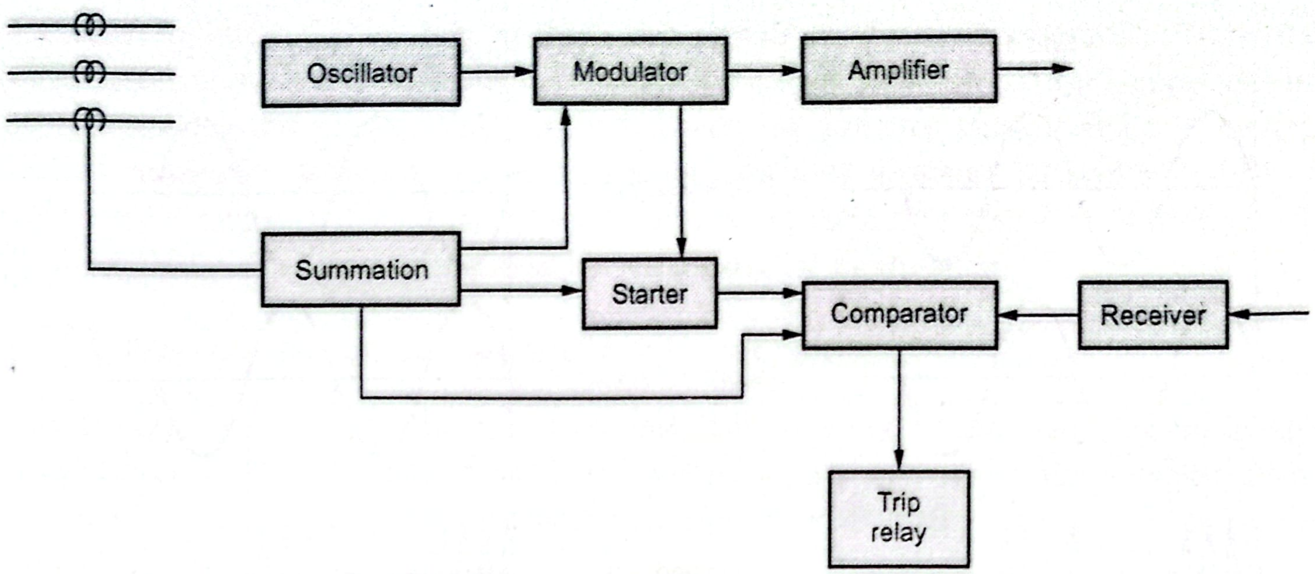

Oscillator
Modulator
Amplifier
Summation
Starter
Comparator
Receiver
Trip relay

Fig. 5.8.5 Block diagram of phase comparison method

In the absence of any fault on the line, the signal is sent for alternate half cycles from each end resulting in continuous signal on the line. For external fault the same condition holds good. If there is an internal fault, the current in one of the lines reverses in phase

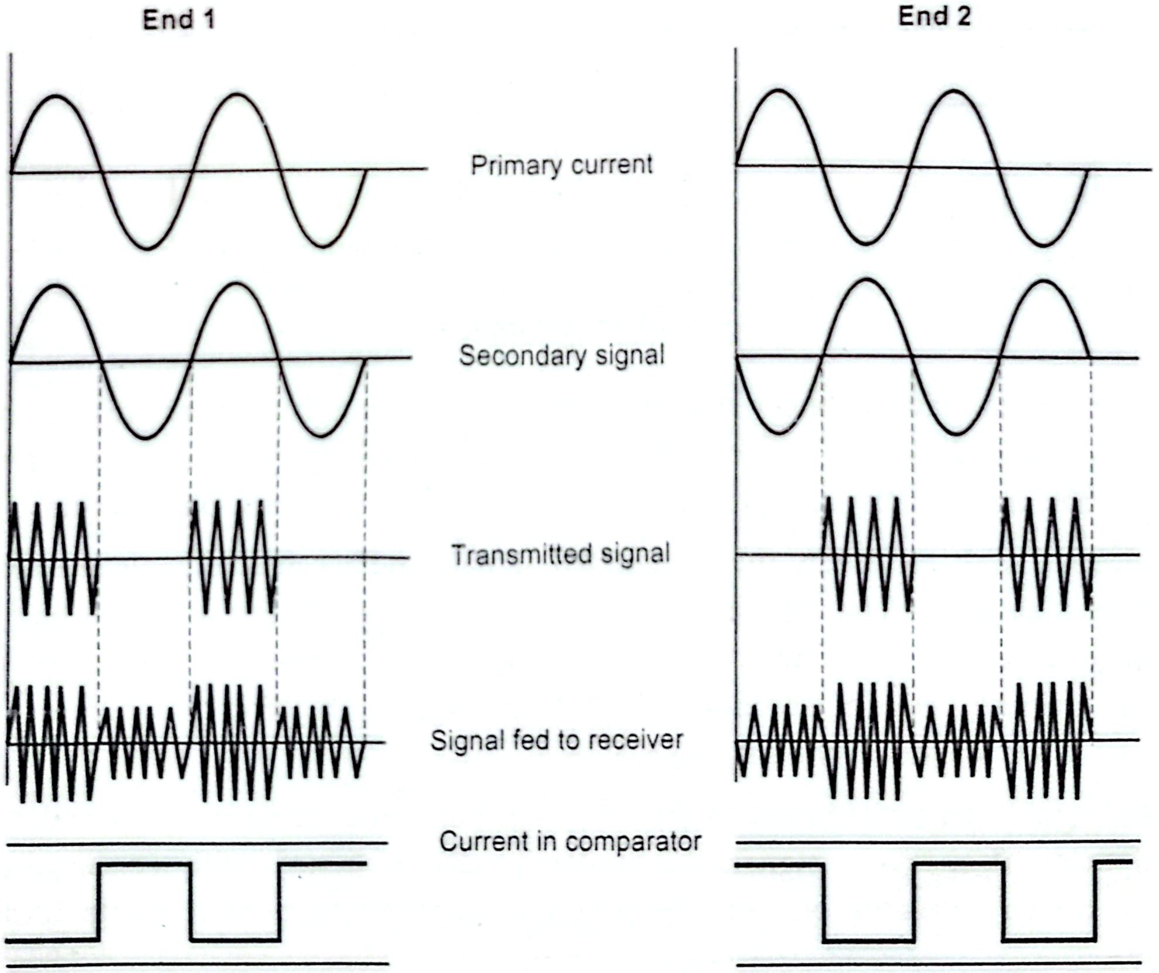

End 1
End 2
Primary current
Secondary signal
Transmitted signal
Signal fed to receiver
Current in comparator

Fig. 5.8.6 (a) External fault

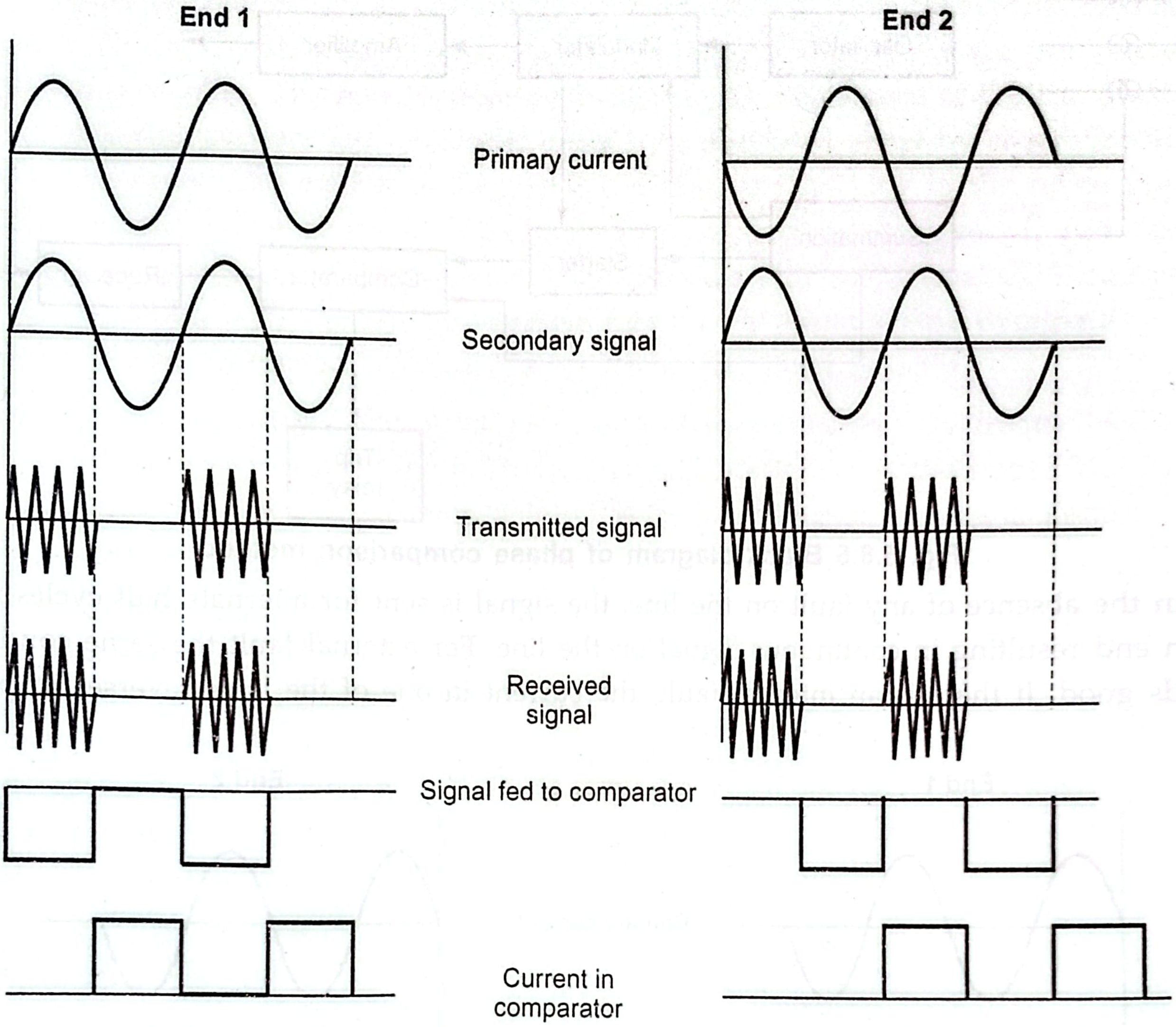

End 1
End 2
Primary current
Secondary signal
Transmitted signal
Received signal
Signal fed to comparator
Current in comparator

Fig. 5.8.6 (b) Internal fault

and remains below fault detector setting resulting in sending the carrier only for half the time. The relay is arranged to sense the absence of signal in the line. When the phase angle between the two signals reaches to a certain set value, the tripping occurs.

For internal fault condition, the transmitted signals and received signals are almost in phase with each other. The comparator compares these signals. For alternate half cycles, the signal is absent so the comparator gives output which operates to trip relay. Various signals in primary circuit, secondary circuit transmitter, receiver comparator during external fault are shown in the Fig. 5.8.6.

Carrier signals are transmitted to the line from both ends. If fault is external then the effect of sum of the two signals is similar to that obtained with continuous high frequency carrier available on line. Protection is designed to remain stable under this condition.

If fault is internal then sum of these two signals produces effects similar to periodic suppression of such a continuous carrier. The time span between the each suppression is proportional to the phase displacement between the primary current at both the ends. Normal angle for which designed protection operates is about 30° below which the protection remains stable. This angle is known as stabilising angle of protection. The high frequency signals are generated by the process of modulation.

5.8.2 Advantages of Carrier Current Protection

With carrier current protection, very fast fault clearing is obtained. The tripping of circuit breakers at both ends of the line takes place in about one to three cycles. Due to this stability of power system is improved. The other advantages of this protection are given below :

1. Simultaneous reclosing of circuit breaker is possible as reclosing signal is sent simultaneously.
2. It prevents shock to the systems as faults are cleared rapidly.
3. It gives easy discrimination for simultaneous faults.
4. During synchronizing power surges, tripping does not occur.
5. For operation of circuit breaker to be fast, faster relaying is necessary which is achieved through carrier aided protection.

The carrier current equipments are used in other applications apart from protection which include communication between two stations. The receiving stations and substations are provided with telephones which are connected to carrier current equipment and conversion of signals is done with the help of carrier current communication. The remote control of power station equipment is possible through carrier equipments using carrier signals. It is also used in telemetering which consists of various electronic equipments that convert the data obtained from transducers into desired form (analog or digital) and transmits it to the control room for its processing using computers.

Review Questions

1. *Draw and explain in detail the block schematic of carrier current protection.* **AU : May-15, Dec.-15, Marks 8**
2. *Explain the phase comparison method of carrier current protection.* **AU : Dec.-15, Marks 8**
3. *State the advantages of carrier current protection.*

5.9 Two Marks Questions with Answers

Q.1 What is meant by time graded protection system ? **AU : Dec.-11**

Ans. : To ensure selectivity of operation the operating time of the protection is increased from the far end of protected circuit towards the generating source.

Q.2 Why busbar protection is needed ? **AU : May-07,08,11, 13,19,22**

Ans. :

1. Fault level at busbar is very high.
2. The stability of the system is affected by the faults in the bus zone.
3. A fault in the busbar causes interruption of supply to a large portion of the system network which causes loss and damage.
4. The equipments connected to the busbar may get damaged.

Q.3 What are the problems associated with busbar differetial protection ? **AU : May-12**

Ans. :

1. Current levels for different circuits are different.
2. Large number of circuits to be protected.
3. Saturation of cores of C.T.s due to d.c. component in short circuit current is possible which produces ratio error.
4. Due to various bus sections the scheme becomes complicated.
5. With large load changes, relay settings need to be changed.

Q.4 State the various possible busbar faults.

Ans. :

1. Failure of insulation due to material deterioration.
2. Failure of circuit breaker.
3. Earth fault due to failure of support insulator.
4. Flashover due to sustained excessive over voltages.
5. Errors in the operation and maintenance of switchgear.
6. Earthquake and mechanical damage.
7. Accidents due to foreign bodies falling on the busbars.

Q.5 What is current grading protection ?

Ans. : The short circuit current along the length of the protected transmission line decreases as the distance of the fault location increases from the power station. Thus the relays near the power station are set to trip at a progressively higher currents. This is called current grading protection.

Q.6 State the limitations of current grading protection scheme.

Ans. :

1. It is difficult for relay to differentiate the fault on either side of a certain section as the difference in currents is small.
2. The magnitude of the fault current cannot be obtained accurately.
3. The accuracy of the relays differ in transient conditions.

Q.7 What is overtravel of the relay ?

Ans. : The overtravel of the relay is the operation of the relay moving elements due to inertia though the actuating force is removed.

Q.8 Write the co-ordination equation used for setting overcurrent relays in time graded protection.

Ans. : The operating time of the relay is graded using the equation,

$$T_A = T_B + CB_2 + 0_A + F$$

where T_A = Operating time of relay at A, T_B = Operating time of relay at B.

CB_2 = Operating time of circuit breaker at B.

0_A = Overtravel time of relay at A and F = Factor of safety.

Q.9 State the disadvantages of non-directional time and current graded methods.

Ans. :

1. The time lag is not desirable for short circuit faults, which is used in these methods.
2. For new connections, the co-ordination of the relays is difficult.
3. For long transmission liens, the method is not suitable as very rapid fault clearing is required.
4. Not suitable for ring mains and interconnected systems.

Q.10 List out the merits of Merz-price protection of feeders.

Ans. :

1. Can be used for parallel as well as ring main systems.
2. Provides instantaneous protection to the ground faults.

Q.11 State the limitations of Merz-price protection of feeders.

Ans. :

1. The C.T.s used must match accurately.
2. The pilot wires must be healthy without discontinuity.
3. Economically not suitable as the cost is high due to long pilot wires.
4. Due to long pilot wires, capacitive effects may affect the operation of the relays.

Q.12 Mention the different protections given to the busbars.

AU : May-06,22, Dec.-07,14,16,17

Ans. : 1. Frame leakage protection 2. Circulating current protection
3. High impedance differential protection 4. Merz-Price protection.

Q.13 Which are the common methods used for the transmission line protection ?

AU : May-07, 18

Ans. : 1. Time graded overcurrent protection 2. Differential protection
3. Distance protection.

Q.14 Which relays are used to protect transmission lines ? **AU : Dec.-10**

Ans. : The Translay relay, impedance type distance relay, differential relay and directional and non-directional overcurrent relays are the relays used to protect transmission lines.

Q.15 Enumerate the concept of ring feeder. **AU : May-14**

Ans. : In the ring feeder the various substations are interconnected by alternate paths in order to form a closed ring. This is shown in the Fig. 5.9.1. The feeder ABCD forms a ring. Such a feeder ensures the reliability of supply.

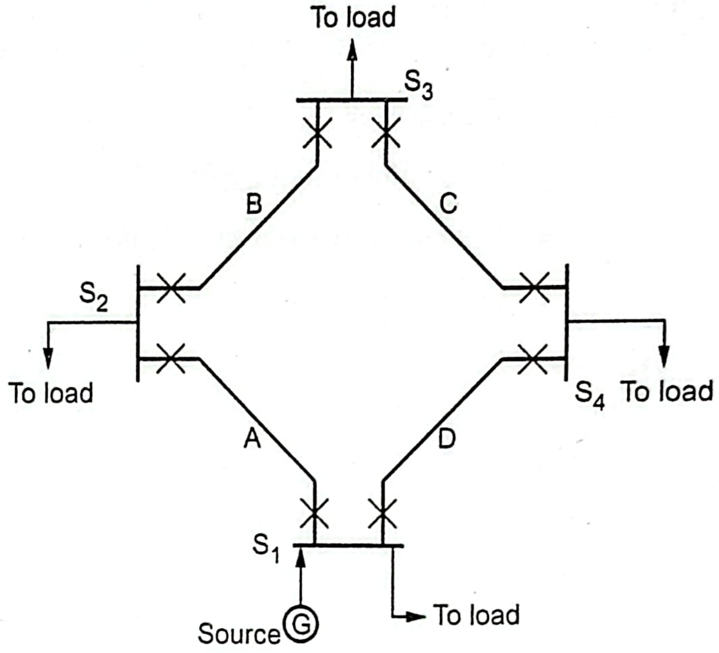


Fig. 5.9.1 Ring feeder

Q.16 Give the examples for unit and non-unit systems of protection. **AU : Dec.-15**

Ans. : The examples of unit system of protection are frame leakage protection, differential protection of alternators, transformers and busbars, pilot wire protection and carrier current protection of transmission lines etc.

The examples of non-unit system of protection are distance protection, time graded protection, current graded protection or both time and current graded protection.

Q.17 Define unit and non-unit system of protection.

Ans. : A system of protection which is capable of detecting and responding to the faults occurring within its own zone of protection is called unit system of protection. It is having absolute discrimination (selectivity). The zone of protection of such system is well defined.

A system which does not have absolute discrimination (selectivity) is called non unit system of protection. It has relative or dependent discrimination.

Q.18 What is the use of line traps in carrier current relaying ? **AU : Dec.-04**

Ans. : The line trap unit is between the busbar and the connection of coupling capacitor to the line. It consists of parallel combination of inductance (L) and capacitance (C) acting as tuned circuit. This circuit offers low impedance to power frequency currents while offers very high impedance to carrier frequency currents which prevents the high frequency carrier to enter in the neighbouring line and carrier currents flow only in the protected line.

Q.19 Which type of protection scheme is preferred for EHV and UHV power lines ?

AU : Dec.-18

Ans. : Mho relay is used for EHV and UHV power lines. The distance protection scheme is widely used for EHV and UHV power lines. Now a days digital distance protection schemes are used.

5.10 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

May-18

Q.1 *With suitable diagrams explain bus bar protection.* **[Section 5.1]** **[8]**

May-19

Q.2 *Discuss the different methods employed for the protection of transmission lines.* **[Section 5.7]** **[13]**

(Regulation 2017)

May-22

Q.3 *Discuss about the pilot protection used for EHV and UHV transmission lines.* **[Section 5.6]** **[13]**

❑❑❑

UNIT IV

6

Static Relays and Numerical Protection

Syllabus

Static relays - Phase, Amplitude Comparators - Synthesis of various relays using static comparators - Block diagram of numerical relays - Overcurrent protection, Transformer differential protection and Distant protection of transmission lines.

Contents

6.1 Introduction

6.2 Block Diagram of a Static Relay ***Dec.-08,10,13,14,17,***
. . . . ***May-13,15,22,*** *· · · · · · · · · · · · Marks 6*

6.3 Comparison of Static and Electromagnetic Relays
. . . . ***May-18, Dec.-18***

6.4 Advantages and Limitations of Static Relays . . ***Dec.-06,17, May-12,13,22,*** *· · Marks 6*

6.5 Comparators

6.6 Amplitude Comparators . . . . ***Dec.-18,*** *· · · · · · · · · · · · · · · Marks 13*

6.7 Phase Comparator

6.8 Duality in Comparators

6.9 Hybrid Comparators

6.10 Mathematical Analysis of Comparators

6.11 Semiconductor Devices used in Static Relays

6.12 Static Overcurrent Relay . . . . ***May-11,18,19, Dec.-17, 18,*** *· Marks 8*

6.13 Directional Static Overcurrent Relay

6.14 Static Differential Relay . . . . ***Dec.-09,*** *· · · · · · · · · · · · · · · · Marks 6*

6.15 Static Distance Relay . . . . ***May-19*** *· · · · · · · · · · · · · · · · Marks 13*

6.16 Synthesis of Mho Relay using Static Comparator . . . . ***Dec.-16, May-22,*** *· · · · · · · · Marks 16*

6.17 Synthesis of Reactance Relay using Static Comparators
. . . . ***May-17,22,*** *· · · · · · · · · · · · · Marks 16*

6.18 Synthesis of Impedance Relay

6.19 Block Diagram of Numerical Relay. . . . . ***May-17, 18, Dec.-22,*** *· · · · · Marks 16*

6.20 Numerical Overcurrent Protection . . . . ***Dec.-16*** *· · · · · · · · · · · · · · · · · Marks 8*

6.21 Numerical Differential Protection of Transformer ***Dec.-16, May-22,*** *· · · · · · · · · Marks 8*

6.22 Numerical Distance protection

6.23 Two Marks Questions with Answers

6.24 University Questions with Answers (Long Answered Questions)

6.1 Introduction

It is seen that the conventional electromagnetic relays use moving parts such as armature in their control circuitry. The relays which do not use moving parts and use the solid state electronic components such as diodes, transistors etc are called **static relays.** The circuits such as comparators, level detectors, zero crossing detectors etc, designed using electronic components are used in the static relays for measurement and comparison of electrical quantities. The static relay is designed in such a way that whenever a quantity under consideration exceeds a particular level, the static circuit produces a response without any moving parts such as armature. This response is then manipulated and given to a tripping circuit which may be electronic or electromagnetic. **Thus static relay response circuit does not have moving parts and made up of electronic components but its tripping circuit may be electronic or electromagnetic.** Let us study the basic elements of a static relay.

6.2 Block Diagram of a Static Relay

AU : Dec.-08,10,13,17, May-13,22

The Fig. 6.2.1 shows the block diagram of a static relay indicating its basic elements.

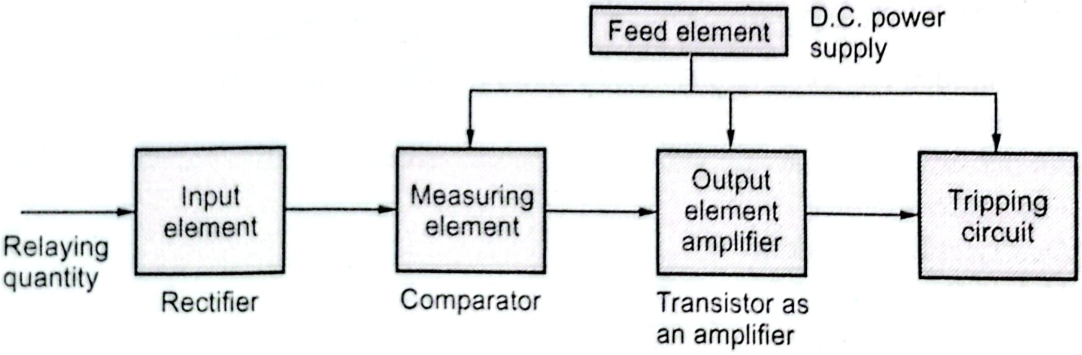


Fig. 6.2.1 Block diagram of a static relay

6.2.1 Input Element

The relaying quantity can be the output of C.T. or P.T. or it may be the output of a transducer or it may be combination of various signals. Thus an electronic circuit such as rectifier is required as an input element to get the input signal in a convenient form before applying it to a measuring element. Some mixing circuits such as op-amp adder may also be required as an input element.

6.2.2 Measuring Element

This is the heart of the static relay. It compares the output of an input element with a set value and decides the signal to be applied to the output element which ultimately drives the tripping circuit. Thus measuring element is a deciding signal generator.

Measuring element can be classified as,

1. Single input device
2. Two input device
3. Multi-input device.

The single input devices, depending on the protection and control schemes are further classified as,

a. Noncritical Repeat Function (All or Nothing Relay) :

As the name suggests, these devices are completely unenergized or energized much higher than the marginal condition required, to produce very fast response. It can be represented as shown in the Fig. 6.2.2. The input R is either zero or too higher than the marginal operating level. Such devices are instantaneous with response time less than 20 ms. The switching power gain associated with them is generally 10^3. Such devices have multiple output contacts.

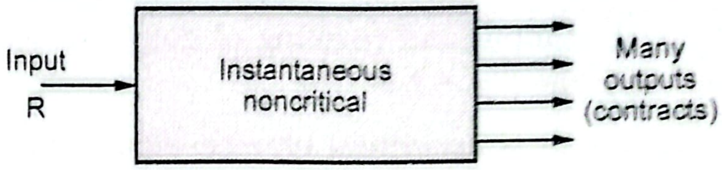


Fig. 6.2.2 Noncritical repeat function

The main functions of such devices in the protection are,

1. To produce final tripping signal to the circuit breaker.
2. To produce signals to perform supplementary functions such as alarming, intertripping etc.
3. To act as intermediate switching stages in a complex protection scheme.

b. Critical Measuring Function :

This device is a sort of on-off controller. It activates when the input signal reaches to some critical level decided by the protection scheme. Such a device is shown in the Fig. 6.2.3.

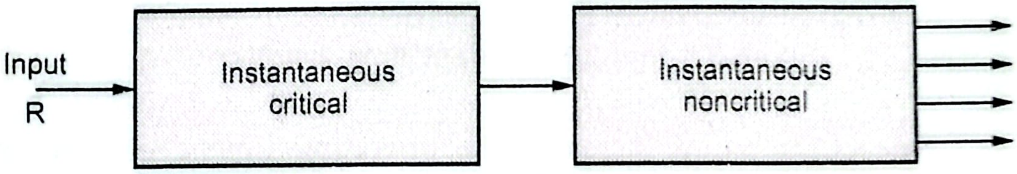


Fig. 6.2.3 Instantaneous critical function

Thus when input R is greater than some critical value P, it operates. While for reset, input R must be less than kP ($k \leq 1$).

It has only one output and switching gain need not be high. The output of such device then can be connected to instantaneous noncritical to obtain multiple outputs.

The various requirements of critical function devices are,

1. High accuracy.
2. Long term consistency.
3. Fast and reliable operation.
4. High controllable reset ratio.

c. Definite or Fixed Time Function :

This is nothing but a delay function element. It produces a define time delay between its input and the output. The delay may be provided between the application of input and activation of output or between removal of input and resetting of output. It is shown in the Fig. 6.2.4.

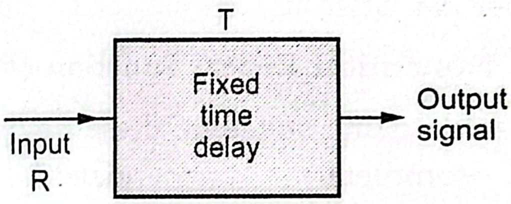


Fig. 6.2.4 Definite time function

The input is noncritical type i.e. either zero or too high than the marginal requirement. Practically charging time of a capacitor is controlled to obtain fixed time delay.

d. Input Dependent Time Function :

This function depends on the input characteristics and decides the time accordingly.

The common form of input dependent time function characteristics is,

$$t = f\left(R^{n}\right) \quad \text{where} \quad R = \text{Input}$$

$$\text{and} \quad n = \text{Negative}$$

The function and its characteristics are shown in the Fig. 6.2.5.

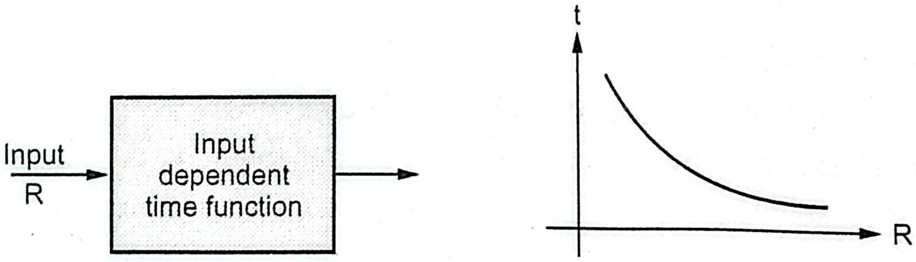


Fig. 6.2.5 Input dependent time function

As n is negative, as the input increases the operating time decreases. So operating time is inversely proportional to some power of the input. The examples of such relays are inverse definite minimum time lag overcurrent and earth fault relays.

The two input devices are very common such as comparators, level detectors etc. while multiple input devices are extension of two input devices to extend the range of characteristics.

6.2.3 Output Element

The signals obtained from the measuring element are required to be amplified before applying to the tripping circuit. Thus output element is an amplifier. Sometimes this element not only amplifies the signals but multiplies them or combines them with other signals to delay them.

6.2.4 Feed Element

The measuring element uses electronic circuits consisting transistors, diodes etc. The output element uses transistor as an amplifier. All these components, circuits alongwith the tripping circuit require d.c. supply for the proper functioning. The feed element provides the d.c. voltage required by the various elements.

Review Questions

1. *Draw and explain the block diagram of static relay.*
AU : Dec.-08,10,13,17, May-13,15,22, Marks 6

2. *Write a note on static relays.* **AU : Dec.-14, Marks 5**

6.3 Comparison of Static and Electromagnetic Relays

AU : May-18, Dec.-18

The Table 6.3.1 gives the comparison of static and electromagnetic relays.

Sr. No.	Static relays	Electromagnetic relays
1.	Moving parts are absent.	Moving parts are present.
2.	Response is very quick.	Response is slower compared to static relays.
3.	Power consumption is small.	Power consumption is more.
4.	The characteristics of components depend on temperature.	The characteristics of components are not dependent on temperature.
5.	Testing and servicing is easy.	Testing and servicing is complicated.
6.	Low short time overload capacity.	Higher short time overload capacity.
7.	Additional d.c. supply is required for electronic components.	Additional d.c. supply is not required.
8.	Less robust.	More robust in nature.
9.	Susceptible to the voltage fluctuations and transients.	Not susceptible to the voltage fluctuations and transients.
10.	Wiring errors are less.	Possibility of wiring errors.

12.	Resetting time and overshoots are reduced.	Resetting time and overshoots are more due to inertia of the mechanical parts.
13.	Single relay can perform various functions and can be programmable.	Programming facility is not available and single relay cannot perform several functions.

Table 6.3.1

Review Question

1. *Compare static relays with electromagnetic relays.* **AU : May-18, Dec.-18, Marks 8**

6.4 Advantages and Limitations of Static Relays

AU : Dec.-06, 17, May-12, 13, 22

The various advantages of static relays are,

1. The moving parts are absent. The moving parts are present only in the actual tripping circuit and not in the control circuit.
2. The burden on current transformers gets considerably reduced thus smaller C.T.s can be used.
3. The power consumption is very low as most of the circuits are electronic.
4. The response is very quick.
5. As moving parts are absent, the minimum maintenance is required. No bearing friction or contact troubles exist.
6. The resetting time can be reduced and overshoots can be reduced due to absence of mechanical inertia and thermal storage.
7. The sensitivity is high as signal amplification can be achieved very easily.
8. The use of printed circuits eliminates the wiring errors and mass production is possible.
9. As electronic circuits can be used to perform number of functions, the wide range of operating characteristics can be obtained, which almost approach to ideal requirements.
10. The low energy levels required in the measuring circuits make the relays smaller and compact in size.
11. The testing and servicing is simplified.
12. Smaller and compact in size.
13. No gravity effect on operation of static relays. Hence can be used in ships, aircrafts etc.

14. A single relay can perform several functions like overcurrent, under voltage, single phasing protection by incorporating respective functional blocks. This is not possible in electromagnetic relays.

The limitations of static relays are,

1. The characteristics of electronic components such as transistors, diodes etc. are temperature dependent. Hence relay characteristics vary with temperature and ageing.
2. The reliability is unpredictable as it depends on a large number of small components and their electrical connections.
3. These relays have low short time overload capacity compared to electromagnetic relays.
4. Additional d.c. supply is required for various transistor circuits.
5. Susceptable to the voltage fluctuations and transients.
6. Less robust compared to electromagnetic relays.

Now a days effect of temperature on the semiconductor devices can be compensated by careful design of the circuits.

Review Question

1. *Mention the advantages and limitations of static relays.*

AU : Dec.-06,17, May-12,13,22, Marks 6

6.5 Comparators

Many relays operate based on the resultant of the comparison of the two quantities. The comparator is that part of relay, which receives two inputs and it produces the output based on the comparison of the two inputs. In some relays the amplitudes of the two quantities, entering and leaving a protected zone are compared. While in some relays the phase angles between the sending end quantities and receiving end quantities are compared. Thus the phase and amplitude comparators are necessary for the relay operation.

The Fig. 6.5.1 shows the classification of comparators used in the relays.

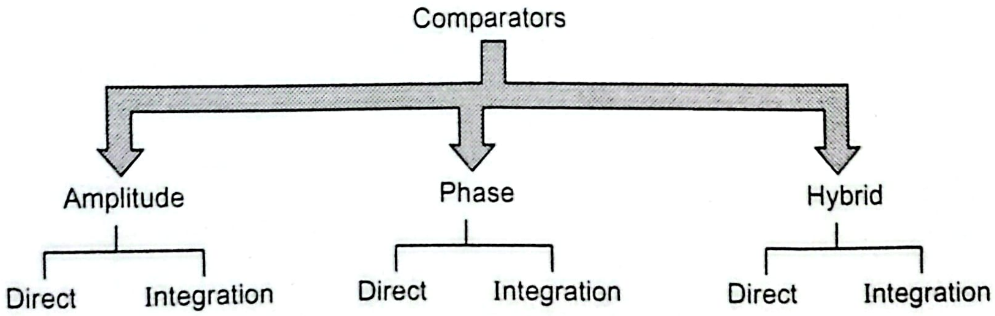


Fig. 6.5.1

6.6 Amplitude Comparators

AU : Dec.-18

An amplitude comparators compare the amplitudes of the two input quantities, irrespective of phase angle of the quantities. The Fig. 6.6.1 shows the basic operation of an amplitude comparator.

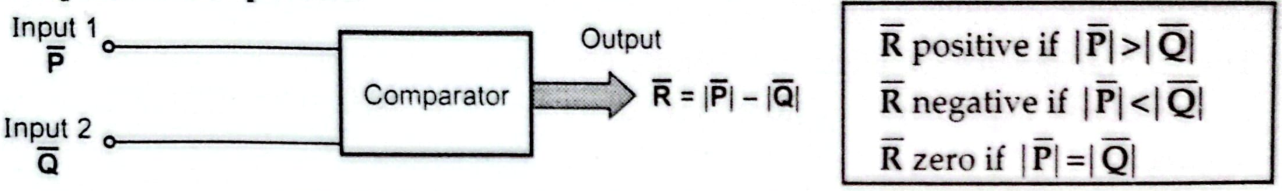

Input 1
$\overline{P}$
Input 2
$\overline{Q}$
Comparator
Output
$\overline{R} = |\overline{P}| - |\overline{Q}|$
$\overline{R}$ positive if $|\overline{P}|>|\overline{Q}|$
$\overline{R}$ negative if $|\overline{P}|<|\overline{Q}|$
$\overline{R}$ zero if $|\overline{P}|=|\overline{Q}|$

Fig. 6.6.1 Basic operation of amplitude comparator

In some comparators, the ratio of the amplitudes is obtained and resultant is decided based on the value of the ratio.

Thus if the comparator obtains $|\overline{P}| / |\overline{Q}|$ i.e. ratio then,

$\overline{R}$ is greater than 1 if $|\overline{P}| > |\overline{Q}|$

$\overline{R}$ is less than 1 if $|\overline{P}| < |\overline{Q}|$

$\overline{R}$ is one if $|\overline{P}| = |\overline{Q}|$

Most of the amplitude comparators are rectifier bridge comparator.

6.6.1 Rectifier Bridge Comparator

The Fig. 6.6.2 shows the rectifier bridge comparator.

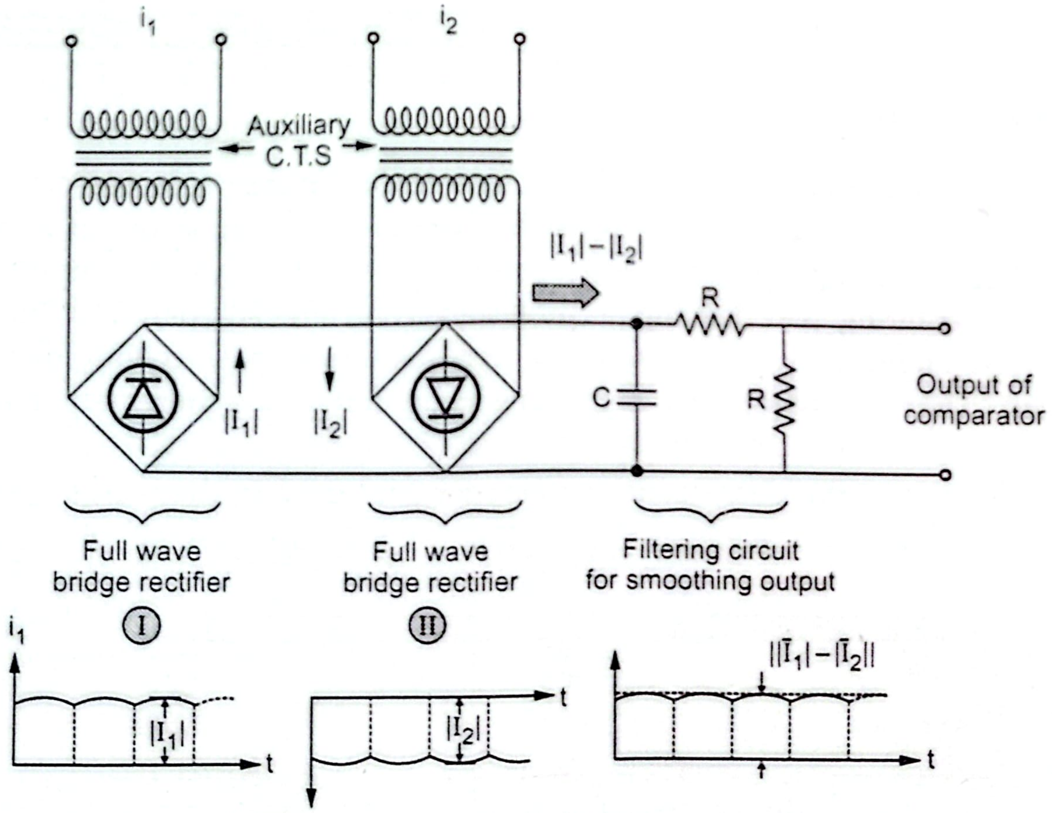

i_1
i_2
Auxiliary C.T.S
$|I_1| - |I_2|$
R
C
R
$|I_1|$
$|I_2|$
Output of comparator
Full wave bridge rectifier
(I)
Full wave bridge rectifier
(II)
Filtering circuit for smoothing output
i_1
$|I_1|$
t
$|I_2|$
t
$||\overline{I}_1| - |\overline{I}_2||$
t

Fig. 6.6.2 Rectifier bridge comparator

The input to comparator are sinusoidal currents derived from auxiliary current transformers. These inputs can be sinusoidal voltages derived from auxiliary potential transformers. Each input is given to a full wave rectifier which rectifies it. The two rectifier circuits are in opposition. The output of the comparator is the difference of the amplitudes of the two input. The output relay is connected in parallel with the two rectifier circuits. A filter circuit is used at the output to make it smoother. Thus output is continuous and a d.c. equivalent to $|I_1|-|I_2|$. When $|I_1|-|I_2|$ exceeds the threshold value defined, the relay operates. The output device can be permanent magnet moving coil relay, sensitive polarised relay or static integrator.

6.6.2 Integrating Amplitude Comparator

In such type of comparator, the output of the comparator is given to an integrator and the circuit integrates the output with time. When such an integrated value reaches the threshold value, the output relay operates.

The block diagram of integrated comparator is shown in the Fig. 6.6.3.

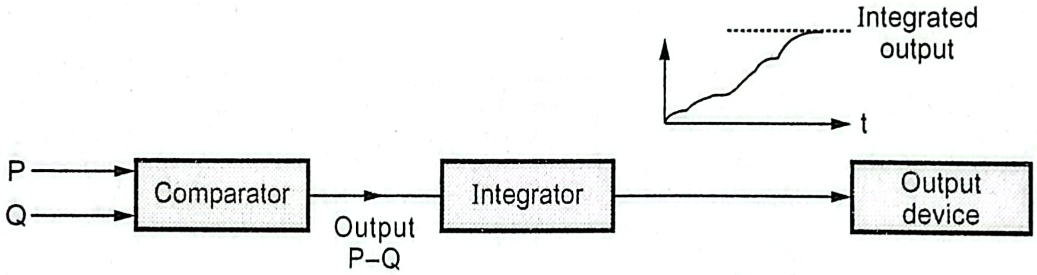


Fig. 6.6.3 Block diagram of integrating comparator

An integrator consists of a capacitor. Depending upon the output of the comparator $|P|-|Q|$, it charges. The voltage across capacitor increases for a positive pulse and decreases for the negative pulse. Thus if P and Q are the rectangular inputs to the comparator, then the output of the comparator and the integrator are shown in The Fig. 6.6.4. Under normal operation, the settings are such that the positive and negative pulses do not allow the integrator output to reach to threshold level.

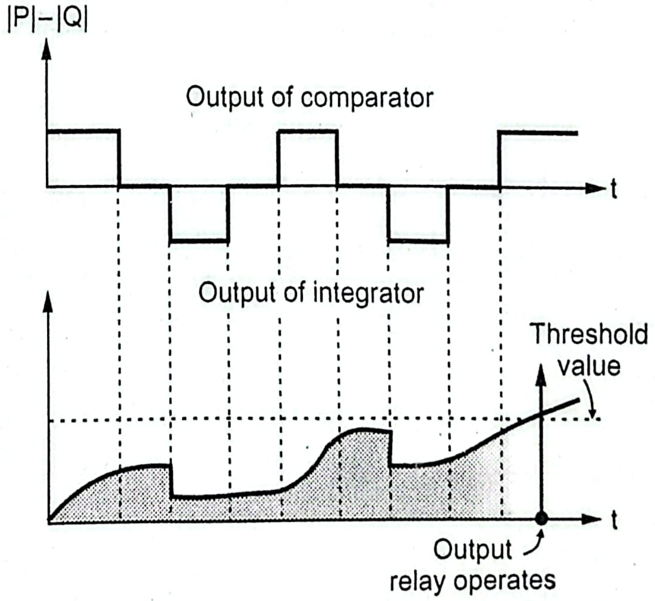


Fig. 6.6.4 Waveforms of integrating type comparator

In some comparators sinusoidal or triangular inputs are also used. In integrated amplitude comparator, a shaper circuit is used after the comparator which converts comparator output to the pulses. These pulses are given to an integrator. The output of integrator is given to a level detector which identifies whether the level is above the threshold value or not. If P > Q then level is above the setting of the level detector while if P < Q then the level detector output is zero. Thus when P > Q, the level detector produces the output which trips the output device.

The block diagram of integrating amplitude comparator and the waveforms for P > Q and P < Q conditions are shown in the Fig. 6.6.5.

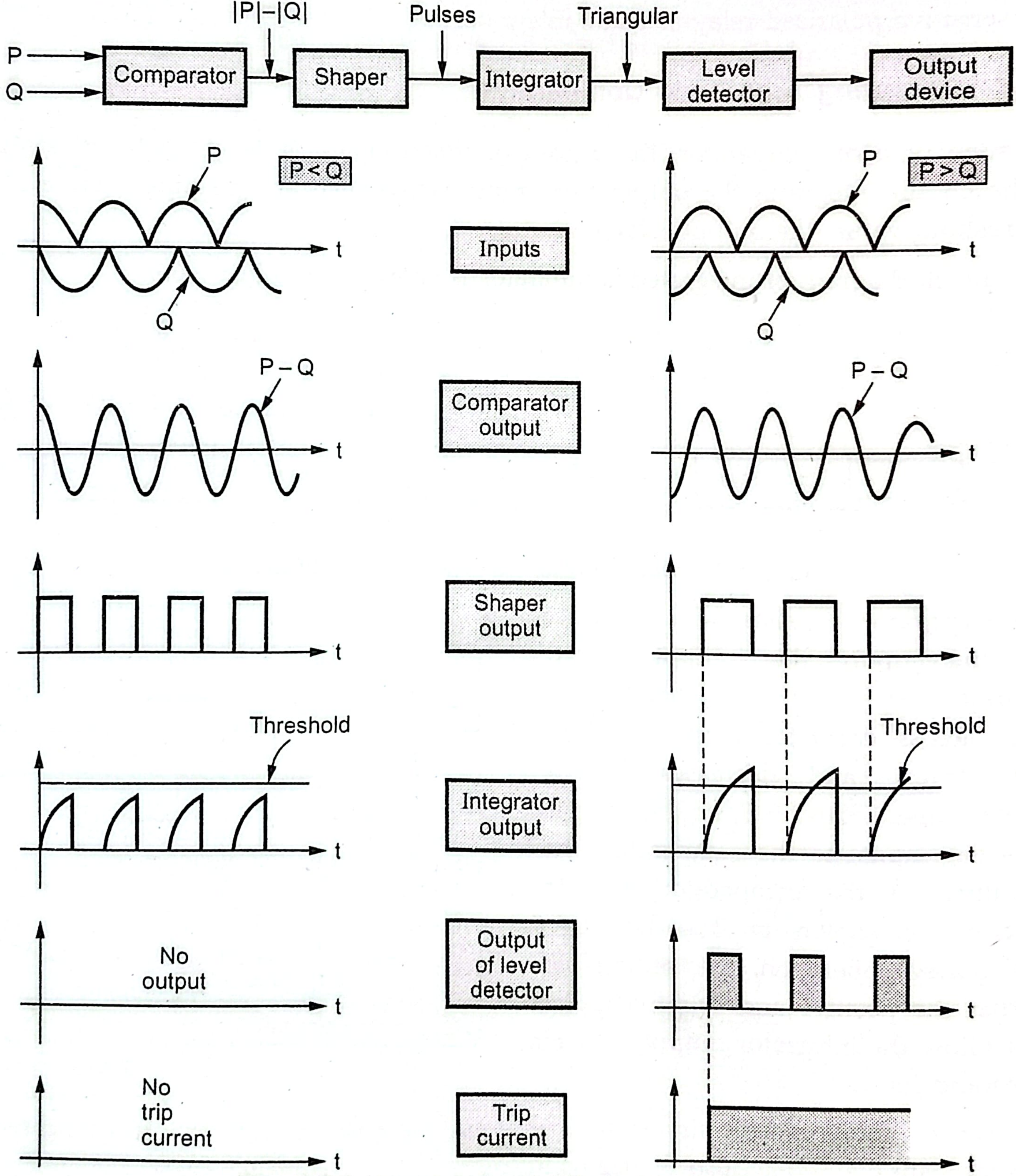

$|\overline{P}|-|\overline{Q}|$
Pulses
Triangular
P
Q
Comparator
Shaper
Integrator
Level detector
Output device
P
P<Q
Q
t
Inputs
P
P>Q
Q
t
P – Q
t
Comparator output
P – Q
t
t
Shaper output
t
Threshold
t
Integrator output
Threshold
t
No output
t
Output of level detector
t
No trip current
t
Trip current
t

Fig. 6.6.5 Integrated amplitude comparator

Review Question

1. *Discuss about amplitude comparators in detail.* **AU : Dec.-18, Marks 13**

6.7 Phase Comparator

In phase comparator the magnitudes of the two inputs are not recognised but only the phase angle ϕ between the two inputs is considered.

In phase comparators, the sinusoidal inputs are converted to rectangular waveforms, before application to the comparator. Thus $[\overline{P}]$ is rectangular equivalent of $\overline{P}$ while $[\overline{Q}]$ is the rectangular equivalent of $\overline{Q}$. This is shown in the Fig. 6.7.1.

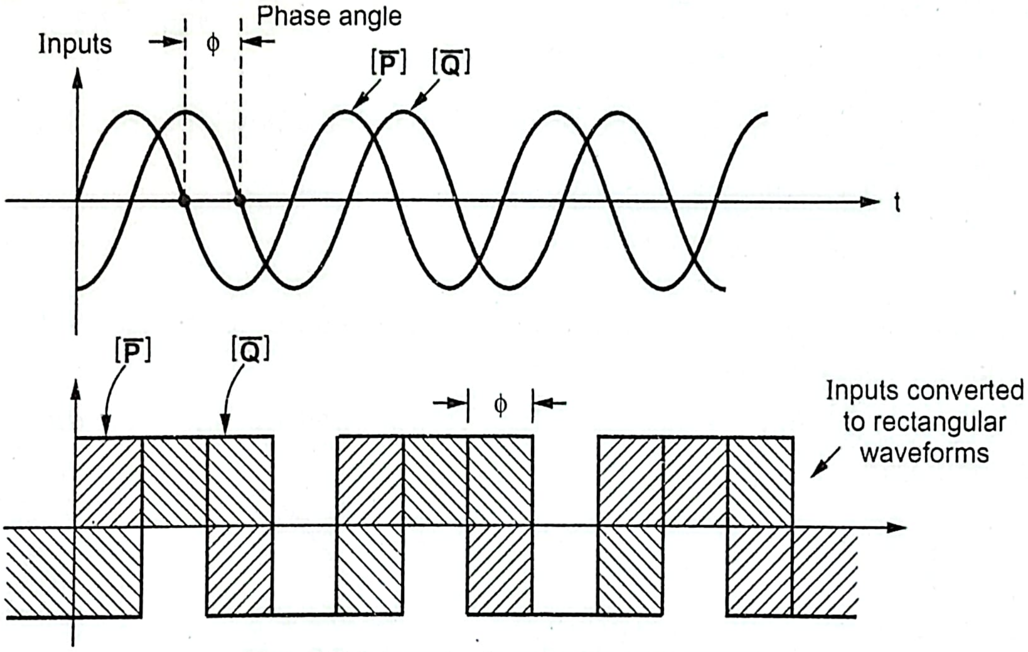

Phase angle
Inputs
ϕ
$[\overline{P}]$ $[\overline{Q}]$
t
$[\overline{P}]$
$[\overline{Q}]$
ϕ
Inputs converted to rectangular waveforms

Fig. 6.7.1 Inputs to phase comparator

The comparator then obtains $[\overline{P}]+[\overline{Q}]$ and $[\overline{P}]-[\overline{Q}]$.

Thus for various values of ϕ,

$$\phi = 0°, |[\overline{P}]+[\overline{Q}]|=|[\overline{P}]-[\overline{Q}]|$$

$$\phi < 90°, |[\overline{P}]+[\overline{Q}]|>|[\overline{P}]-[\overline{Q}]|$$

$$\phi > 90°, |[\overline{P}]+[\overline{Q}]|<|[\overline{P}]-[\overline{Q}]|$$

Hence if comparator is designed so as to obtain the difference of magnitudes of $|[\overline{P}]+[\overline{Q}]|$ and $|[\overline{P}]-[\overline{Q}]|$ then the phase angle ϕ can be obtained. The output of the phase comparater is in terms of the magnitude only. These comparators are widely used for all practical directional, distance, differential and carrier relays as these can be readily adopted with logic circuit. For obtaining ϕ, various techniques such as vector product, splitting and coincidence circuits are used in practice.

In integrating type phase comparator, the output of the basic phase comparator is given to an integrator and level detector. Thus it operates similar to an integrated amplitude comparator as output of the phase detector is basically interms of an amplitude.

6.7.1 Sine and Cosine Type Phase Comparators

As seen earlier, the phase comparators recognise only the phase angle between the two inputs. One of the two inputs is polarizing i.e. reference input while the other is measured input.

1. Sine type phase comparator :

The Fig. 6.7.2 shows the sine type phase comparator.

$\overline{P}$ = Reference input

$\overline{Q}$ = Measured input

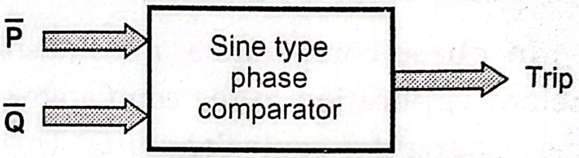

$\overline{P}$
$\overline{Q}$
Sine type phase comparator
Trip

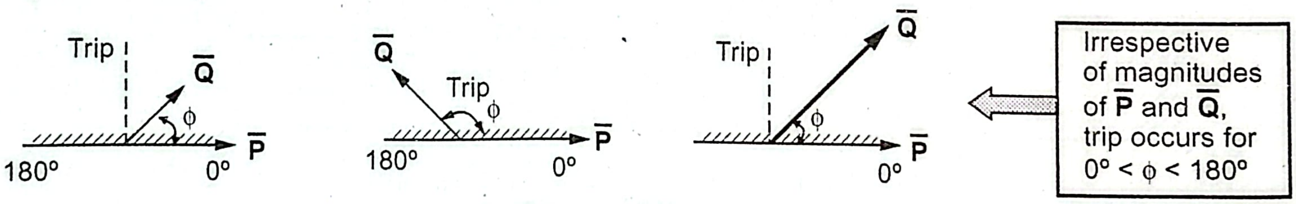
Fig. 6.7.2

The phase angle between the two inputs can be obtained as $\angle\left(\dfrac{\overline{P}}{\overline{Q}}\right)$ and the sine type phase comparator follows the trip law,

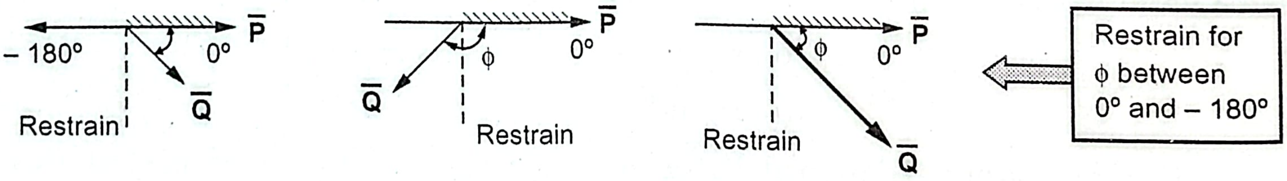
$$\text{If } 0° < \left[\angle\left(\frac{\overline{P}}{\overline{Q}}\right)\right] < 180° \text{ then trip otherwise restrain}$$

Generally reference input is selected as reference hence its phase is 0° hence its position is along 0° i.e. positive x-axis direction.

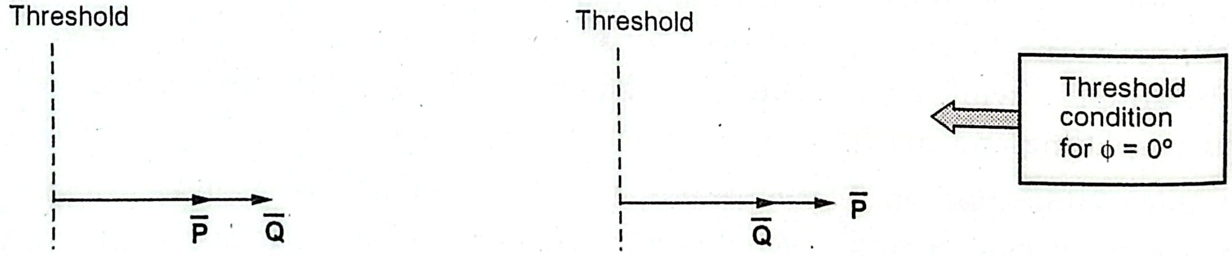
The Fig. 6.7.3 (a), (b) and (c) shows the trip, restrain and threshold conditions for sine type phase comparator.


Trip
$\overline{Q}$
ϕ
180°
0°
$\overline{P}$
$\overline{Q}$
Trip
ϕ
$\overline{P}$
180°
0°
Trip
$\overline{Q}$
ϕ
0°
$\overline{P}$
Irrespective of magnitudes of $\overline{P}$ and $\overline{Q}$, trip occurs for 0° < ϕ < 180°

(a) Trip condition


– 180°
0°
$\overline{P}$
$\overline{Q}$
Restrain
$\overline{P}$
0°
ϕ
$\overline{Q}$
Restrain
$\overline{P}$
ϕ
0°
Restrain
$\overline{Q}$
Restrain for ϕ between 0° and – 180°

(b) Restrain condition


Threshold
$\overline{P}$
$\overline{Q}$
Threshold
$\overline{P}$
$\overline{Q}$
Threshold condition for ϕ = 0°

(c) Threshold condition

Fig. 6.7.3 Sine type phase comparator

2. Cosine type of phase comparator

The Fig. 6.7.4 shows the cosine type of phase comparator.

Due to the cosine nature of the inputs, the trip law changes as,

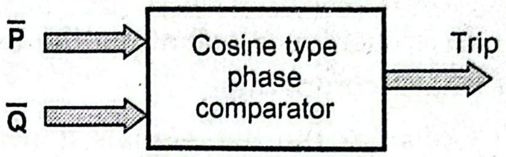
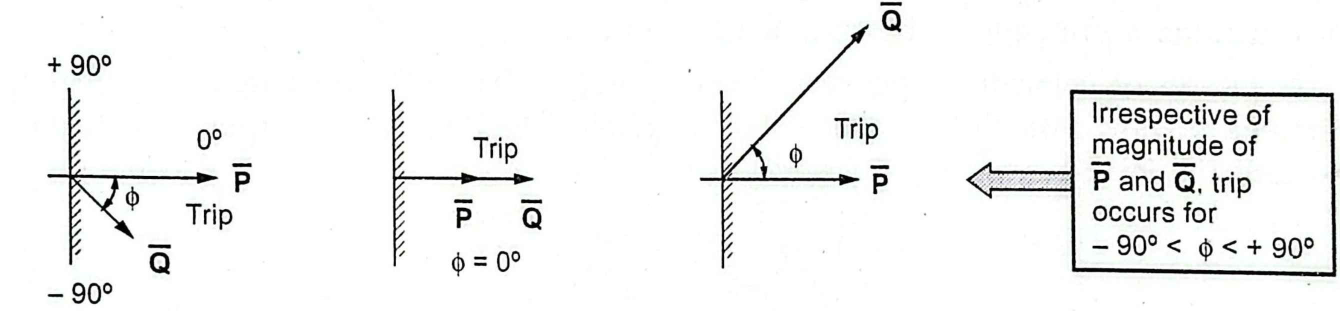

$\bar{P}$
$\bar{Q}$
Cosine type phase comparator
Trip

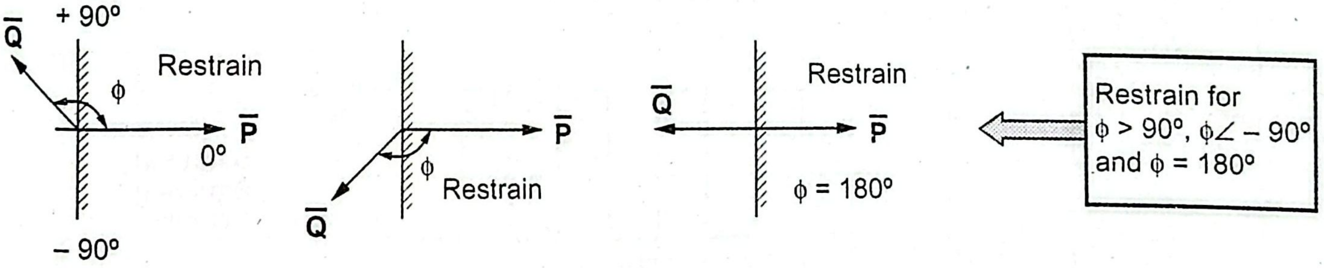
Fig. 6.7.4

$$\text{If } -90^\circ < \left[\angle\left(\frac{\bar{P}}{\bar{Q}}\right)\right] < +90^\circ \text{ then trip otherwise restrain}$$

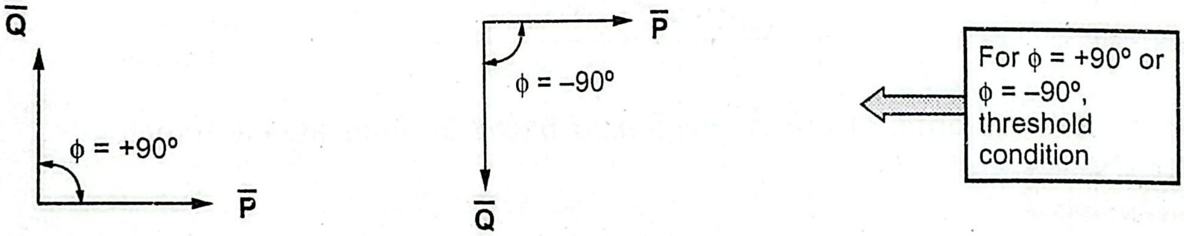
The Fig. 6.7.5 (a), (b) and (c) shows the trip, restrain and threshold conditions for cosine type comparator.


+ 90°
0°
$\bar{P}$
ϕ
Trip
$\bar{Q}$
– 90°
Trip
$\bar{P}$
$\bar{Q}$
ϕ = 0°
$\bar{Q}$
Trip
ϕ
$\bar{P}$
Irrespective of magnitude of $\bar{P}$ and $\bar{Q}$, trip occurs for – 90° < ϕ < + 90°

(a) Trip condition


$\bar{Q}$
+ 90°
Restrain
ϕ
$\bar{P}$
0°
– 90°
$\bar{P}$
ϕ
Restrain
$\bar{Q}$
$\bar{Q}$
Restrain
$\bar{P}$
ϕ = 180°
Restrain for ϕ > 90°, ϕ∠ – 90° and ϕ = 180°

(b) Restrain condition


$\bar{Q}$
ϕ = +90°
$\bar{P}$
$\bar{P}$
ϕ = –90°
$\bar{Q}$
For ϕ = +90° or ϕ = –90°, threshold condition

(c) Threshold condition

Fig. 6.7.5 Cosine type phase comparator

In any case, the comparator reacts to phase angle between $\bar{P}$ and $\bar{Q}$ and does not recognize the relative magnitudes of the two inputs.

6.7.2 Coincidence Principle in Phase Comparators

In coincidence technique the overlapping of the two signals is used for the operation of phase comparator.

Consider the two signals P and Q which are overlapped for the period ϕ. The period of coincidence is denoted by shading in the Fig. 6.7.6 (a). The coincidence circuit gives output for this period of coincidence. This is then given to the squaring circuit which produces pulses including tripping pulses and blocking pulses as shown in the Fig. 6.7.6 (b).

The output of squaring circuit is given to an integrator. The output of an integrator increases depending on the pulses. This is shown in the Fig. 6.7.6 (c). This output is given to a level detector. Once it exceeds a certain level L, level detector gives actuating signal to output stage which triggers the trip circuit. The block diagram and waveforms of coincidence principle is shown in the Fig. 6.7.6.

If period of coincidence between P and Q is less than 90° then output of integrator remains always less than L while if it is greater than 90° then output of integrator exceeds the level L.

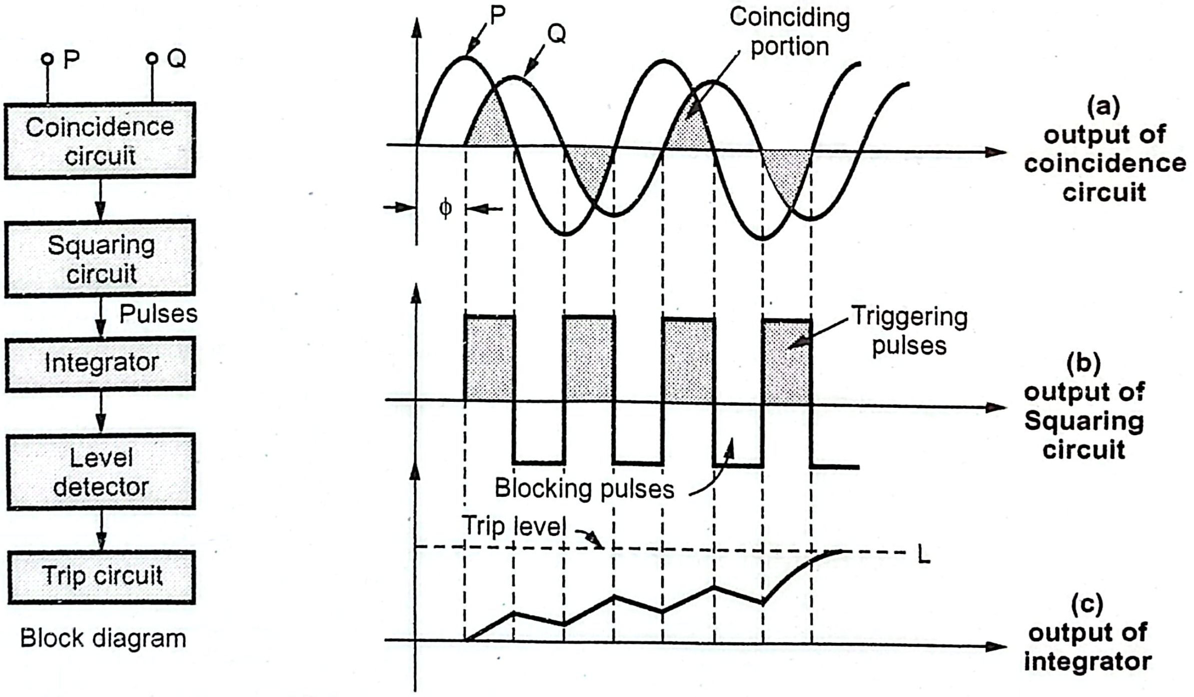

P
Q
Coincidence circuit
Squaring circuit
Pulses
Integrator
Level detector
Trip circuit
Block diagram
P
Q
Coinciding portion
ϕ
(a) output of coincidence circuit
Triggering pulses
(b) output of Squaring circuit
Blocking pulses
Trip level
L
(c) output of integrator

Fig. 6.7.6 Waveforms of phase comparator based on coincidence principle

Review Questions

1. *Discuss about phase comparators in detail.*
2. *Draw neat diagrams to demonstrate 'trip', 'restrain' and threshold' conditions for the sine and cosine type of phase comparators.*
3. *Discuss the coincidence principle used in phase comparators.*

6.8 Duality in Comparators

According to the principle of duality if inputs of amplitude comparator are modified, they become suitable as the phase comparator inputs and viceversa. This is concept of duality in comparators.

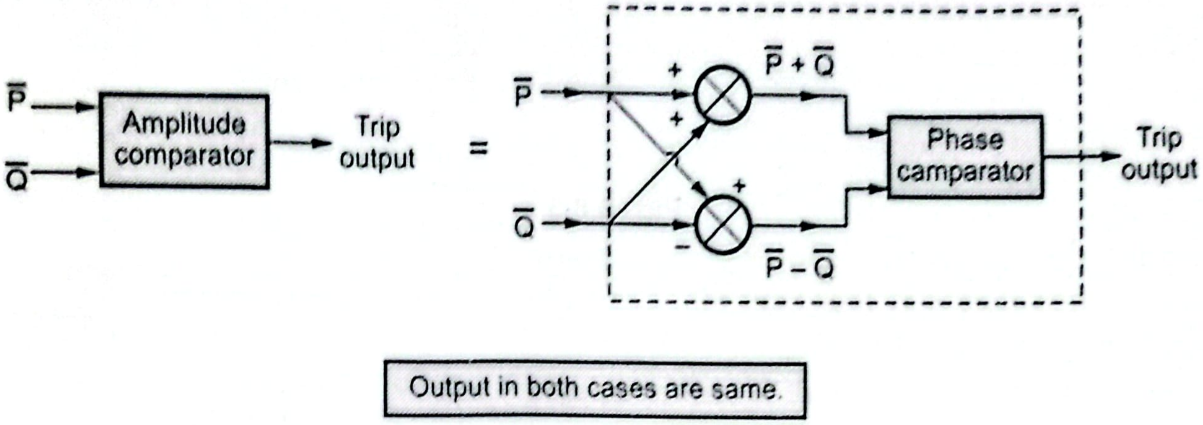

$\bar{P}$
$\bar{Q}$
Amplitude comparator
Trip output
=
$\bar{P}$
$\bar{Q}$
+
+
+
−
$\bar{P}+\bar{Q}$
$\bar{P}-\bar{Q}$
Phase camparator
Trip output
Output in both cases are same.

Fig. 6.8.1 Principle of duality in comparators

Let $\bar{P}$ and $\bar{Q}$ be the original inputs to an amplitude comparator. Derive the signals $\bar{P}+\bar{Q}$ and $\bar{P}-\bar{Q}$. These signals then can be used as the inputs to the phase comparator. Then the output of the phase comparator remains same as the output of the original amplitude comparator. This is called duality in comparators. This is shown in the Fig. 6.8.1.

Similarly if $\bar{P}_1$ and $\bar{Q}_1$, are the original inputs to a phase comparator then if $\bar{Q}_1+\bar{P}_1$ and $\bar{Q}_1-\bar{P}_1$ are generated and applied to amplitude comparator then the output of amplitude comparator is same as the output of original phase comparator. This is shown in the Fig. 6.8.2.

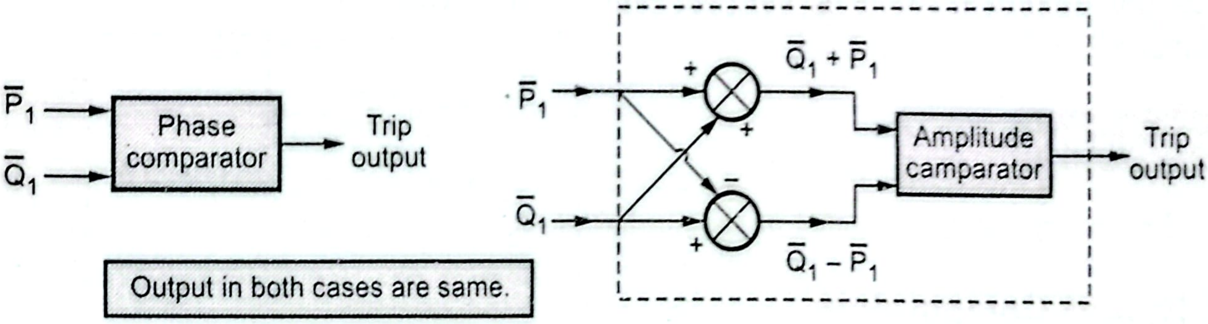

$\bar{P}_1$
$\bar{Q}_1$
Phase comparator
Trip output
$\bar{P}_1$
$\bar{Q}_1$
+
+
−
+
$\bar{Q}_1+\bar{P}_1$
$\bar{Q}_1-\bar{P}_1$
Amplitude camparator
Trip output
Output in both cases are same.

Fig. 6.8.2 Principle of duality in comparators

The duality theorem states that the two signals obtained by adding and subtracting the inputs of a comparator are suitable as the inputs to its dual. When such signals are applied to its dual then the output remains unchanged.

Graphical representation of principle of duality

Let $\bar{P}$ and $\bar{Q}$ be the inputs to an amplitude comparator such that $|\bar{P}| > |\bar{Q}|$ hence comparator output trips.

Generate the signals $\bar{R}_1 = \bar{P}+\bar{Q}$ and $\bar{R}_2 = \bar{P}-\bar{Q}$ as shown in the Fig. 6.8.3.

If $\bar{R}_1$ and $\bar{R}_2$ are applied as the inputs to a phase comparator then as $\phi < 90°$ between them, the output of phase comparator trips.

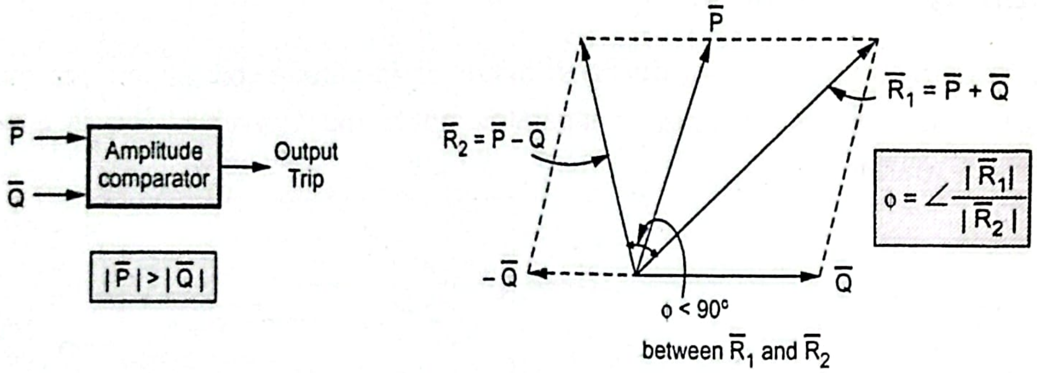

$\overline{P}$
$\overline{Q}$
Amplitude comparator
Output Trip
$|\overline{P}| > |\overline{Q}|$
$\overline{P}$
$\overline{R}_1 = \overline{P} + \overline{Q}$
$\overline{R}_2 = \overline{P} - \overline{Q}$
$\phi = \angle \frac{|\overline{R}_1|}{|\overline{R}_2|}$
$-\overline{Q}$
$\overline{Q}$
$\phi < 90°$
between $\overline{R}_1$ and $\overline{R}_2$

Fig. 6.8.3

Consider the inputs $\overline{R}_1$ and $\overline{R}_2$ to a phase comparator such that ϕ is less than 90°. Generate the signals $\overline{R}_2 + \overline{R}_1$ and $\overline{R}_2 - \overline{R}_1$.

The generated signals $\overline{T}_1$ and $\overline{T}_2$ are such that $|\overline{T}_1| > |\overline{T}_2|$

If these signals are applied to an amplitude comparator then as $|\overline{T}_1| > |\overline{T}_2|$, the output trips.

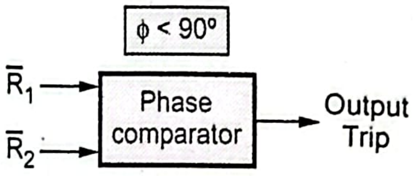

$\phi < 90°$
$\overline{R}_1$
$\overline{R}_2$
Phase comparator
Output Trip

Fig. 6.8.4

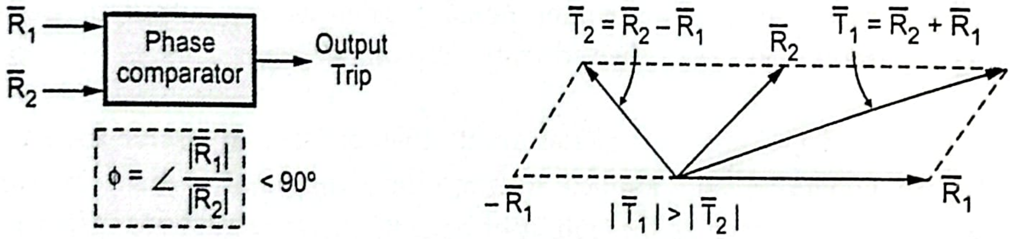

$\overline{R}_1$
$\overline{R}_2$
Phase comparator
Output Trip
$\phi = \angle \frac{|\overline{R}_1|}{|\overline{R}_2|} < 90°$
$\overline{T}_2 = \overline{R}_2 - \overline{R}_1$
$\overline{R}_2$
$\overline{T}_1 = \overline{R}_2 + \overline{R}_1$
$-\overline{R}_1$
$|\overline{T}_1| > |\overline{T}_2|$
$\overline{R}_1$

Fig. 6.8.5

Thus the duality theorem is verified. Similar cases can be analyzed for $|\overline{P}| < |\overline{Q}|$ and $\phi > 90°$.

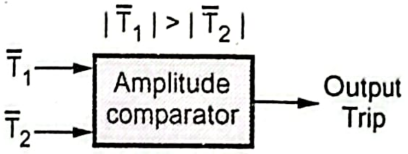

$|\overline{T}_1| > |\overline{T}_2|$
$\overline{T}_1$
$\overline{T}_2$
Amplitude comparator
Output Trip

Fig. 6.8.6

Review Question

1. *Explain the concept of duality in static comparators.*

6.9 Hybrid Comparators

In hybrid comparators both amplitude as well as phase of the input signals is considered. The inputs are given to phase comparator and then output of phase comparator and one input is given to an amplitude comparator. The level detector stage and output device are connected at the output of the amplitude comparator.

The Fig. 6.9.1 shows the block diagram of the hybrid comparator.

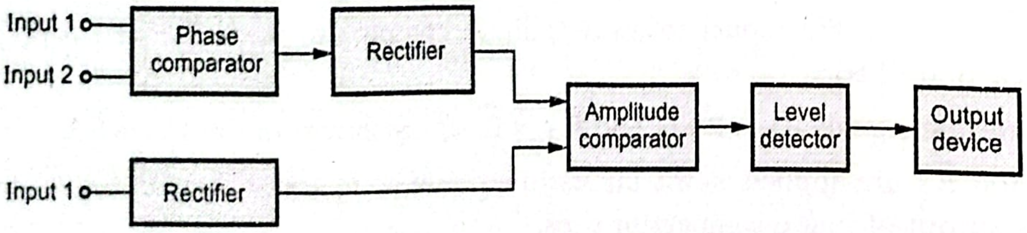

Input 1
Input 2
Phase comparator
Rectifier
Amplitude comparator
Level detector
Output device
Input 1
Rectifier

Fig. 6.9.1 Block diagram of hybrid comparator

6.10 Mathematical Analysis of Comparators

Let S_1 and S_2 are the two input signals derived from current or potential transformers of the power system. In many cases, signals from both current and potential transformers are derived and mixed with the help of mixing device. Thus,

$$\left.\begin{aligned} \bar{S}_1 &= K_1 \bar{P} + \bar{K}_2 \bar{Q} \\ \bar{S}_2 &= K_3 \bar{P} + \bar{K}_4 \bar{Q} \end{aligned}\right\} \quad \text{...(6.10.1)}$$

Where K_1 and K_3 are scalar constants while $\bar{K}_2$ and $\bar{K}_4$ are the vector constants having angles θ_2 and θ_4 respectively. The $\bar{P}$ and $\bar{Q}$ are the signals obtained from auxiliary devices of the power system.

The mixed signals $\bar{S}_1$ and $\bar{S}_2$ are used as the inputs of comparator as shown in the Fig. 6.10.1.

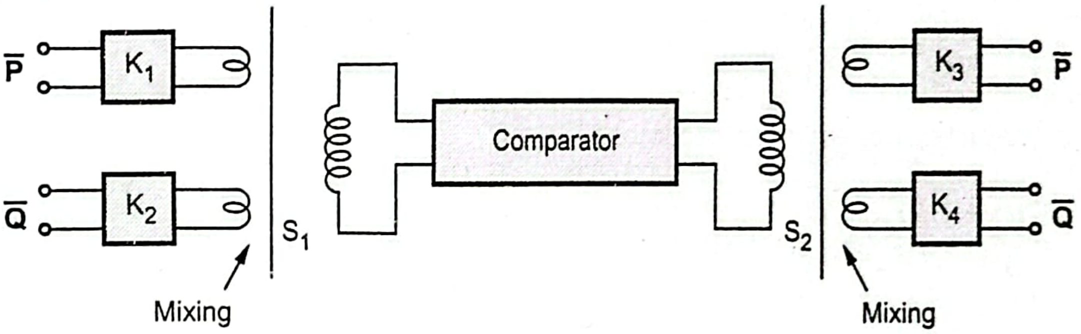


Fig. 6.10.1 Comparator using mixed signals

Let $\bar{P}$ be the reference vector $(|P|\angle 0^\circ)$ while the $\bar{Q}$ lagging $\bar{P}$ by angle ϕ $(|Q|\angle -\phi^\circ)$. Thus the equation (6.10.1) gets modified as,

$$\left.\begin{aligned} S_1 &= K_1|P|+K_2|Q|\{\cos(\theta_2-\phi)+j\sin(\theta_2-\phi)\} \\ S_2 &= K_3|P|+K_4|Q|\{\cos(\theta_4-\phi)+j\sin(\theta_4-\phi)\} \end{aligned}\right\} \quad \text{...(6.10.2)}$$

6.10.1 Analysis of Amplitude Comparator

Let the criteria for the operation is $|S_1| \geq |S_2|$. At the threshold, the magnitudes of S_1 and S_2 must be same. Hence equating the magnitudes of S_1 and S_2,

$$[K_1|P|+K_2|Q|\cos(\theta_2-\phi)]^2+[K_2|Q|\sin(\theta_2-\phi)]^2$$

$$= [K_3|P|+K_4|Q|\cos(\theta_4-\phi)]^2+[K_4|Q|\sin(\theta_4-\phi)]^2 \quad \text{...(6.10.3)}$$

$$\therefore\ K_1^2|P|^2+2K_1K_2|P||Q|\cos(\theta_2-\phi)+K_2^2|Q|^2\cos^2(\theta_2-\phi)+K_2^2|Q|^2\sin^2(\theta_2-\phi)$$

$$= K_3^2|P|^2+2K_3K_4|P||Q|\cos(\theta_4-\phi)+K_4^2|Q|^2\cos^2(\theta_4-\phi)+K_4^2|Q|^2\sin^2(\theta_4-\phi)$$

$$\therefore\ (K_1^2-K_3^2)|P|^2+2|P||Q|\{K_1K_2\cos(\theta_2-\phi)-K_3K_4\cos(\theta_4-\phi)\}+|Q|^2(K_2^2-K_4^2)=0 \quad \text{...(6.10.4)}$$

Dividing by $(K_2^2-K_4^2)|P|^2$

$$\frac{|Q|^2}{|P|^2}+2\left|\frac{Q}{P}\right|\left\{\frac{K_1K_2\cos(\theta_2-\phi)-K_3K_4\cos(\theta_4-\phi)}{K_2^2-K_4^2}\right\}+\frac{K_1^2-K_3^2}{K_2^2-K_4^2}=0$$

Using $\cos(\theta_2 - \phi) = \cos\theta_2 \cos\phi + \sin\theta_2 \sin\phi$

and $\cos(\theta_4 - \phi) = \cos\theta_4 \cos\phi + \sin\theta_4 \sin\phi$

$$\left|\frac{Q}{P}\right|^2 + 2\left|\frac{Q}{P}\right|\left\{\frac{(K_1K_2\cos\theta_2 - K_3K_4\cos\theta_4)\cos\phi + (K_1K_2\sin\theta_2 - K_3K_4\sin\theta_4)\sin\phi}{K_2^2 - K_4^2}\right\} + \frac{K_1^2 - K_3^2}{K_2^2 - K_4^2} = 0$$

Let $A_0 = \dfrac{K_1K_2\cos\theta_2 - K_3K_4\cos\theta_4}{K_2^2 - K_4^2}$ $\quad B_0 = \dfrac{K_1K_2\sin\theta_2 - K_3K_4\sin\theta_4}{K_2^2 - K_4^2}$

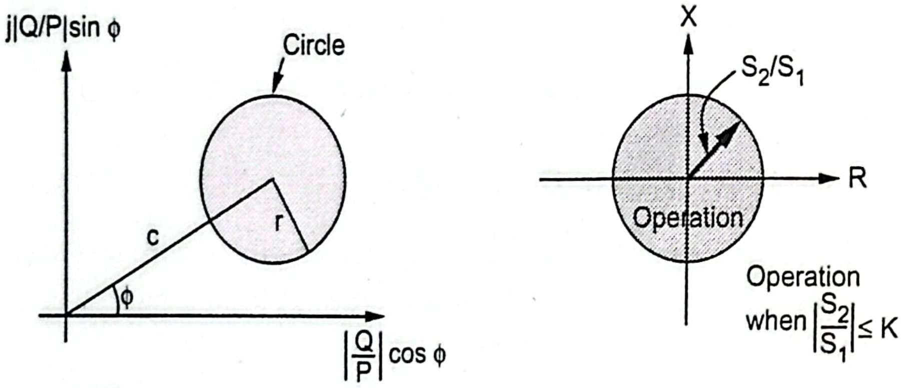
$$C_0 = \frac{K_1^2 - K_3^2}{K_2^2 - K_4^2}$$

Thus characteristic equation becomes,

$$\boxed{\left|\frac{Q}{P}\right|^2 + 2\left|\frac{Q}{P}\right|[A_0\cos\phi + B_0\sin\phi] + C_0 = 0} \qquad \ldots(6.10.5)$$

This equation represents a circle on the β-plane with $|Q/P|\cos\phi$ and $j\,|Q/P|\sin\phi$ as co-ordinates. This circle is shown in the Fig. 6.10.2.

The various values for the circle are,



(a) Circle characteristics (b) Application in relay

Fig. 6.10.2 Threshold characteristics of comparator

$$r = \text{Radius} = \frac{\sqrt{K_2^2K_4^2 + K_2^2K_3^2 - 2K_1K_2K_3K_4\cos(\theta_2 - \theta_4)}}{K_2^2 - K_4^2} \qquad \ldots(6.10.6)$$

$$c = \frac{\sqrt{K_1^2K_2^2 + K_3^2K_4^2 - 2K_1K_2K_3K_4\cos(\theta_2 - \theta_4)}}{K_2^2 - K_4^2} \qquad \ldots(6.10.7)$$

6.10.2 Analysis of Phase Comparator

Let S_1 and S_2 are the two signals to be compared.

$$S_1 = |S_1| \angle\alpha \quad \text{and} \quad S_2 = |S_2| \angle\beta$$

Then relay operates when the product '$S_1\, S_2$' is positive. This product is maximum when both the signals are in phase. The conventional relay characteristics can be obtained with the symmetrical phase comparator with the condition,

$$(\alpha - \beta) = \pm 90^\circ$$

Taking tan of both sides, the threshold condition is,

$$\tan(\alpha - \beta) = \pm\infty \quad \text{i.e.} \quad \frac{\tan\alpha - \tan\beta}{1 + \tan\alpha \tan\beta} = \pm\infty$$

$$\therefore \ 1 + \tan\alpha \tan\beta = 0 \qquad \ldots(6.10.8)$$

For complex number $a + jb$, the phase angle is given by $\tan\theta = b/a$. Thus from equation (6.10.2),

$$\tan\alpha = \frac{K_2|Q|\sin(\theta_2 - \phi)}{K_1|P| + K_2|Q|\cos(\theta_2 - \phi)}$$

and

$$\tan\beta = \frac{K_4|Q|\sin(\theta_4 - \phi)}{K_3|P| + K_4|Q|\cos(\theta_4 - \phi)}$$

Using in equation (6.10.8),

$$1 + \frac{K_2|Q|\sin(\theta_2 - \phi)}{K_1|P| + K_2|Q|\cos(\theta_2 - \phi)} \times \frac{K_4|Q|\sin(\theta_4 - \phi)}{K_3|P| + K_4|Q|\cos(\theta_4 - \phi)} = 0$$

$$\therefore \ K_1K_3|P|^2 + K_2K_3|P||Q|\cos(\theta_2 - \phi) + K_1K_4|P||Q|\cos(\theta_4 - \phi)$$

$$+ K_2K_4|Q|^2\cos(\theta_2 - \phi)\cos(\theta_4 - \phi) + K_2K_4|Q|^2\sin(\theta_2 - \phi)\sin(\theta_4 - \phi) = 0$$

$$\therefore \ K_1K_3|P|^2 + [K_2K_3\cos(\theta_2 - \phi) + K_1K_4\cos(\theta_4 - \phi)]\,|P||Q| + K_2K_4|Q|^2\cos(\theta_2 - \phi_4) = 0 \qquad \ldots(6.10.9)$$

Dividing by $K_2K_4|P|^2\cos(\theta_2 - \theta_4)$,

$$\left|\frac{Q}{P}\right|^2 + \left|\frac{Q}{P}\right| \frac{[K_2K_3\cos(\theta_2 - \phi) + K_1K_4\cos(\theta_4 - \phi)}{K_2K_4\cos(\theta_2 - \theta_4)} + \frac{K_1K_3}{K_2K_4\cos(\theta_2 - \theta_4)} = 0$$

$$\left|\frac{Q}{P}\right|^2 + \left|\frac{Q}{P}\right| \left\{\frac{(K_1K_4\cos\theta_4 + K_2K_3\cos\theta_2)\cos\phi + (K_1K_4\sin\theta_4 + K_2K_3\sin\theta_2)\sin\phi}{K_2K_4\cos(\theta_2 - \theta_4)}\right\}$$

$$+ \frac{K_1K_3}{K_2K_4\cos(\theta_2 - \theta_4)} = 0$$

Let

$$A'_0 = \frac{K_1K_4 \cos\theta_4 + K_2K_3 \cos\theta_2}{K_2K_4 \cos(\theta_2 - \theta_4)} \quad B'_0 = \frac{K_1K_4 \sin\theta_4 + K_2K_3 \sin\theta_2}{K_2K_4 \cos(\theta_2 - \theta_4)}$$

$$C'_0 = \frac{K_1K_3}{K_1K_4 \cos(\theta_2 - \theta_4)}$$

The characteristics equation becomes,

$$\left|\frac{Q}{P}\right|^2 + \left|\frac{Q}{P}\right|[A'_0 \cos\phi + B'_0 \sin\phi] + C'_0 = 0 \qquad \ldots(6.10.10)$$

This is the equation of a circle on the β-plane with,

$$r = \text{Radius} = \frac{\sqrt{K_1^2K_4^2 + K_2^2K_3^2 - 2K_1K_2K_3K_4 \cos(\theta_2 - \theta_4)}}{2K_2K_4 \cos(\theta_2 - \theta_4)} \qquad \ldots(6.10.11)$$

and

$$c = \frac{\sqrt{K_1^2K_4^2 + K_2^2K_3^2 + 2K_1K_2K_3K_4 \cos(\theta_2 - \theta_4)}}{2K_2K_4 \cos(\theta_2 - \theta_4)} \qquad \ldots(6.10.12)$$

Practically in the relay design, at least one of the constants K_1, K_2, K_3, K_4 is zero and two of the other three are equal. The angle of the two vector constants is also kept same. Thus it is easier to set the threshold condition for the operation of the relay.

Review Questions

1. *Derive the characteristic equation for the phase comparator.*
2. *Derive the characteristic equation for amplitude comparator.*

6.11 Semiconductor Devices used in Static Relays

The various electronic components, devices and circuits which are commonly used in static relays are,

1. **Semiconductor diodes :** This includes the conventional p-n junction diode, zener diode, avalanche diode and the circuits using these diodes such as rectifiers, regulators, references etc.
2. **Transistors :** This includes Bipolar Junction Transistors (BJT) and Field Effect Transistors (FET). The transistors are used as amplifiers or as switches in the static relays. The direct coupled amplifiers using transistors are also used in the static relays.
3. **Unijunction transistor :** The device UJT having negative resistance characteristics is often used to obtain relaxation oscillator, the output of which is used to trigger SCR.

4. **Thyristor family :** This includes various two and three terminal and four layer electronic devices such as Silicon Controlled Rectifier (SCR), triac, diac, Silicon Controlled Switch (SCS). Such devices are used in static relays to obtain high speed switching characteristics.

5. **Logic circuits :** Most of the relays are bistable devices i.e. they are operated in two stable states either ON or OFF. The logic circuit also has two states high i.e. ON and low i.e. OFF. Hence logic circuits play an important role in the static relays.

6. **Filter circuits :** The RC and LC filters are also used in static relays after rectifiers to obtain smoothing of d.c. voltage generated. To obtain fast smoothing instead of conventional capacitor filter, the phase splitting before the rectification is used in static relays.

7. **Multivibrators :** The various multivibrators using transistors are used to produce square waveforms in static relays. The diode clippers also can be used to obtain square waveforms.

8. **Time delay circuits :** The variety of time delay circuits such as delay lines, RC circuits, timer circuits, resonant circuits using transistors, thyristors and ICs are used in static relays. Depending upon the requirement of time delay, the particular circuit is chosen. The delay lines are used for shorter delays while RC charging and discharging circuits are used for longer delays. The time delays of the order of micro secs to hours can be achieved using such time delay circuits.

9. **Level detectors :** In static relays, it is necessary to detect the operating levels of various signals and used it to produce the necessary actuating signals. The level detector circuits using the diodes, rectifier and RC elements are commonly used in static relays.

10. **Analog circuits :** The op-amp available in IC form is very common in building analog circuits such as adder, subtractor, differentiator, integrator, inverting amplifier, noninverting amplifier etc. Op-amp also can be used to obtain the circuits like zero crossing detector, Schmitt trigger etc. All such circuits are used in various types of static relays.

Review Question

1. *Discuss the various semiconductor devices used in the static relays.*

6.12 Static Overcurrent Relay

AU : May-11,18,19, Dec.-17,18

This is nothing but instantaneous overcurrent relay. The Fig. 6.12.1 shows the block diagram of static time current relay.

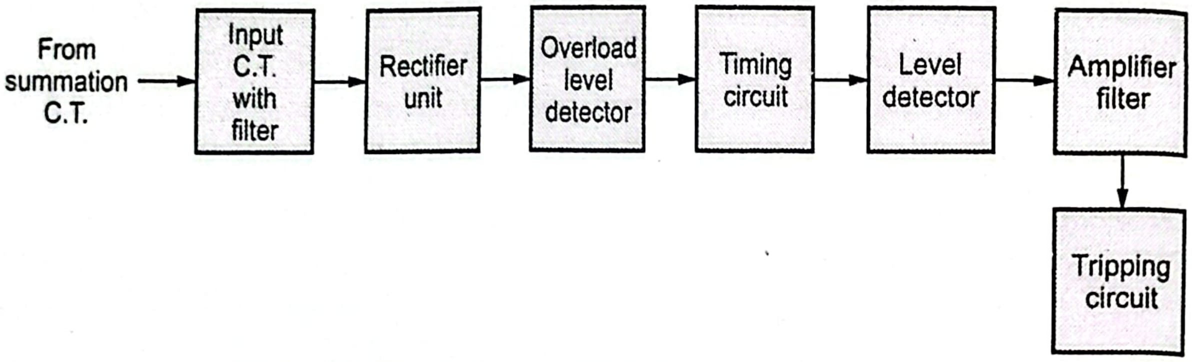


Fig. 6.12.1 Block diagram of time current static relay

The secondaries of line C.T.s are connected to the summation circuit. The output of summation C.T. is given to the input C.T. The input C.T. is called auxiliary C.T. which has taps on the primary for selecting the required pickup and current range. Then the output of auxiliary C.T. is rectified and smoothened. It is then applied to overload level detector and RC timing circuit. When the voltage across the timing capacitor reaches to a critical value then it triggers the level detector. The output of the level detector is amplified as per the requirement and given to the tripping circuit. This operates the output device. The charging of capacitor in a timing circuit is achieved by a voltage derived from C.T. current. This voltage is obtained across a nonlinear resistor by passing rectified current through it. The proper selection of nonlinear resistor and RC timing circuit allows to obtain desired shape of time current characteristics of the static relay.

The current at which the level detector trips is called **threshold current** denoted as $I_{threshold}$. Thus for an overcurrent relay,

when $I_{in} < I_{threshold}$, level detector does not trip

when $I_{in} \geq I_{threshold}$, level detector trips

6.12.1 Static Time-Current Characteristics

The time-current characteristics is inverse type of characteristics and given by the expression,

$$\boxed{t = \frac{K(TMS)}{I^n - I_p^n}}$$

where t = Time of operation in seconds

K = Design constant of relay

TMS = Time multiplier setting

I = Tap current multiplier

I_p = Multiple of tap current at which pickup occurs n = Characteristic index of relay

The shape of the characteristics and degree of inverse nature is standardized. According to British standards,

For standard inverse characteristics (IDMT),

$$K \times (TMS) = 0.14, \quad n = 0.02 \quad \text{and} \quad I_p = 1\ A$$

For standard very inverse characteristics,

$$K \times (TMS) = 13.5, \quad n = 1 \quad \text{and} \quad I_p = 1\ A$$

For extremely inverse characteristics,

$$K \times (TMS) = 80, \quad n = 2 \quad \text{and} \quad I_p = 1\ A$$

The characteristics are shown in the Fig. 6.12.2.

It can be seen that the curve is asymptotic about both the axes. Due to this, there exists minimum pickup current below which relay can not be operated. While there exists minimum definite time of operation below which it can not be reduced.

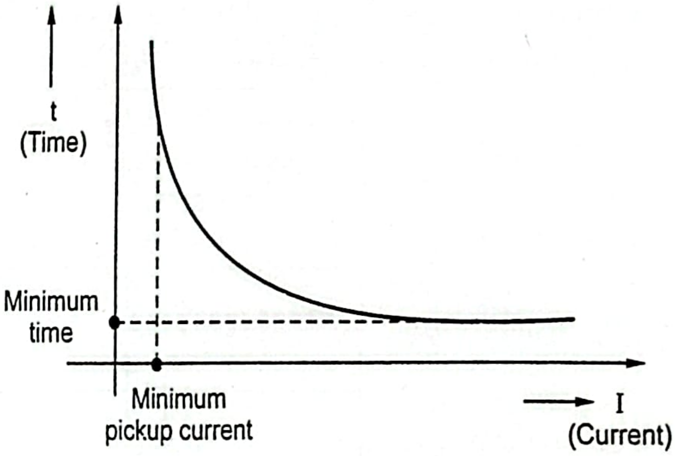


Fig. 6.12.2 Inverse time-current characteristics

6.12.2 Static Instantaneous Overcurrent Relay

The detailed circuit diagram of instantaneous static overcurrent relay is shown in the Fig. 6.12.3.(See Fig. 6.12.3 on next page).

The auxiliary transformer gives output voltage proportional to the fault current. The main circuit is protected from the voltage surges by using R_1C_1 circuit at the input. This is **surge protector**. The output voltage from the transformer is then rectified and smoothened using capacitor filter C_2. The level of this voltage is compared with the voltage level decided by zener diode Z_{D1}. This zener limits the rectified voltage to a safe value though the fault current is very high. Part of this voltage, as decided by the potentiometer P is compared with the breakdown voltage of another zener diode Z_{D2}. When the rectified voltage is greater than voltage of Z_{D2}, the transistor Q_1 conducts. This increases drop across R_2 due to which Q_2 conducts. This energizes the trip coil T_c of the relay. When the trip coil opens, it develops high reverse voltage (back e.m.f.). To protect Q_2 from such a high back e.m.f., a diode D is connected across the trip coil. With the help of potentiometer P different pick up values can be obtained.

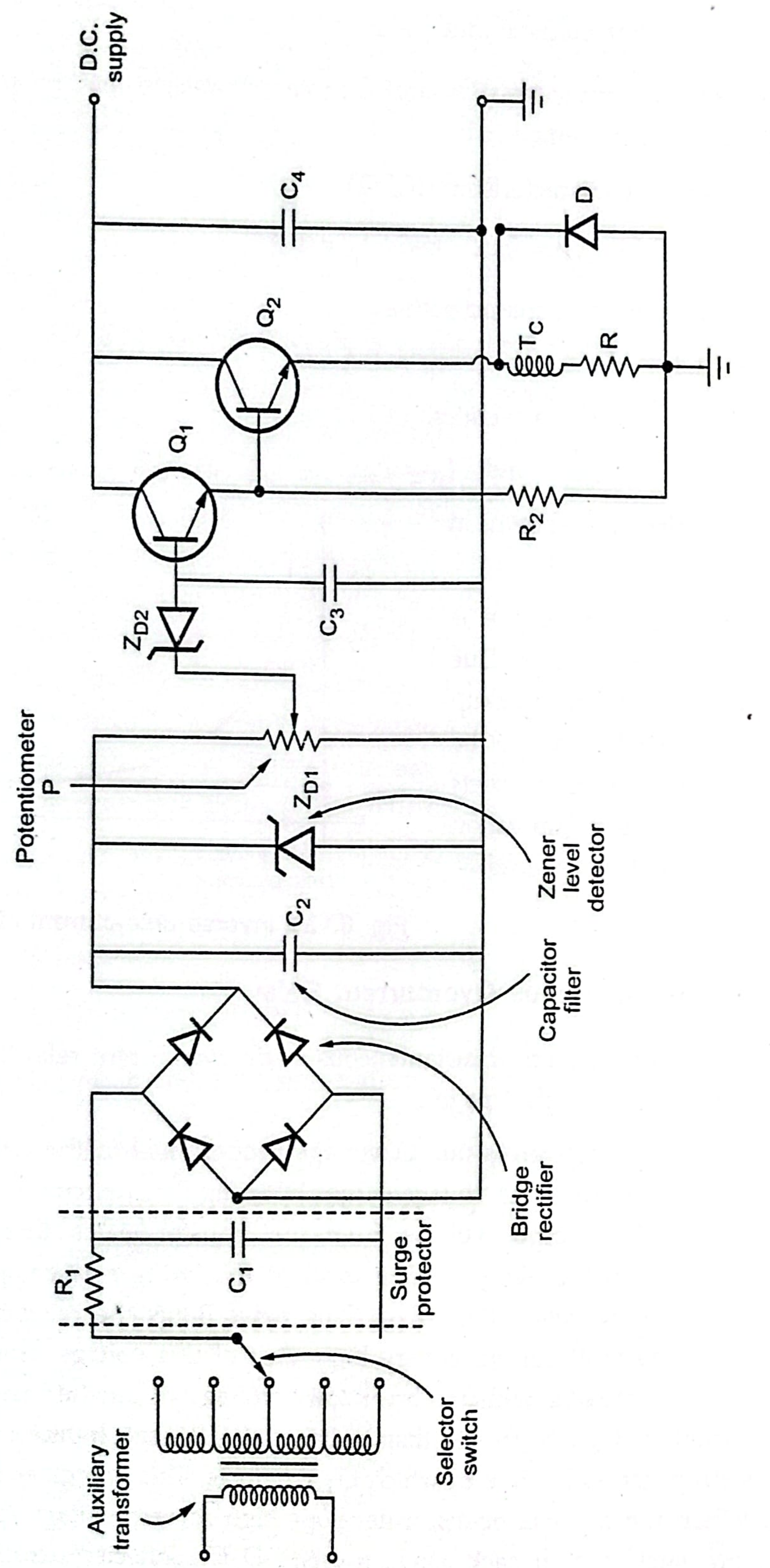

D.C. supply
C_4
D
Q_2
T_C
R
Q_1
R_2
Z_{D2}
C_3
Potentiometer P
Z_{D1}
Zener level detector
C_2
Capacitor filter
Bridge rectifier
R_1
C_1
Surge protector
Selector switch
Auxiliary transformer

Fig. 6.12.3 Static overcurrent relay

6.12.3 Inverse Time-Current Relay

The Fig. 6.12.4 shows the circuit diagram of static inverse time-current relay.

(See Fig. 6.12.4 on next page)

Under normal conditions, Q_1 gets biasing from d.c. supply applied through R_4 and P_2 and conducts. Hence capacitor C is short circuited. When fault current exceeds the pick up value set by the potentiometer P_2 and selector switch then the transistor Q_1 becomes OFF. The capacitor C starts charging through R_3 and P_1 by the voltage developed across R_1. This charging time varies as per the severity of the fault. More severe is the fault, more is the voltage developed across R_1 and less is the time for charging capacitor C to a critical level. When voltage across the capacitor reaches to a predetermined level set by the potentionmenter P_3 then the transistor Q_3 conducts. This energizes the trip coil and the circuit breaker opens. The diode D protects the transistor from the high reverse voltage. Thus more is the fault current, less is the time required to operate relay hence it is inverse time-current relay.

Review Questions

1. *Draw and explain the block diagram of static time overcurrent relay along with its time-current characteristics.* **AU : Dec.-17, May-18,19, Marks 16**
2. *Discuss the static inverse time-current relay.*
3. *Describe the principle and operation of instantaneous overcurrent static relay with neat block diagram.* **AU : May-11, Dec.-18, Marks 8**

6.13 Directional Static Overcurrent Relay

The directional relay is nothing but a directional power relay which operates when the power in the circuit flows in a particular direction. Thus it requires to sense the system voltage as well as the system current.

The Fig. 6.13.1 shows block diagram of the directional static overcurrent relay.

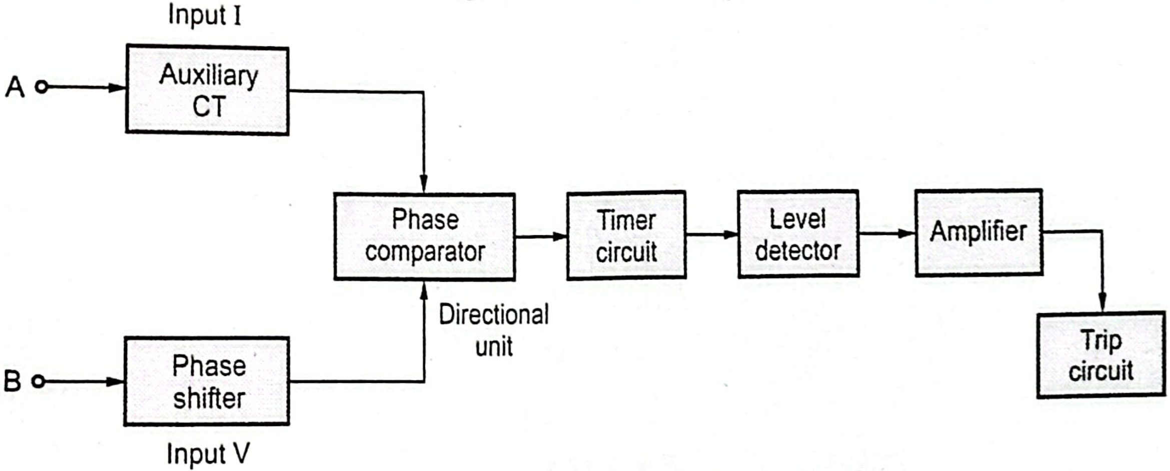


Fig. 6.13.1 Directional static overcurrent relay

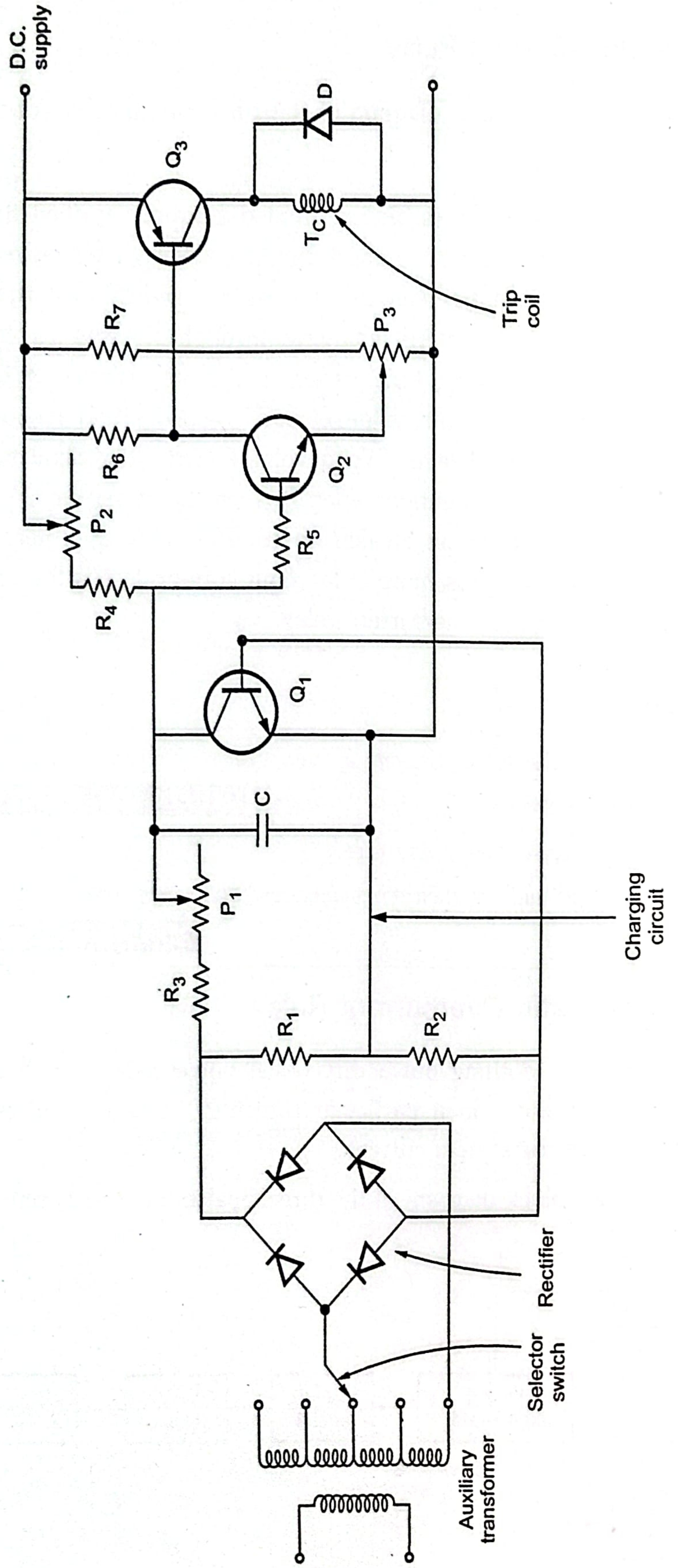

D.C. supply
Q$_3$
D
T$_C$
Trip coil
R$_7$
P$_3$
R$_6$
Q$_2$
P$_2$
R$_5$
R$_4$
Q$_1$
C
P$_1$
Charging circuit
R$_3$
R$_1$
R$_2$
Rectifier
Selector switch
Auxiliary transformer

Fig. 6.12.4

The input A is proportional to the system current supplied to a directional unit through auxiliary transformer. The input B is proportional to the system voltage, supplied to a directional unit through phase shifter.

The phase comparator compares the phase angle between the two inputs. Let this angle is ϕ while the relay characteristics angle is θ. Let I_p be the current setting magnitude. Then the relay operates when,

$$I_p \leq I \cos(\phi - \theta)$$

The output of the phase comparator is applied to a level detector through timer if time delay is required. The output of the level detector is amplified and given to the trip circuit.

The phase comparator is generally of two types,

1. Hall effect generator which is popularly used in Russian countries.
2. Rectifier bridge type comparator which is popularly used in European countries.

The static directional overcurrent relays are very sensitive and directional unit can be made reliable down to 1 % of the system voltage.

Review Question

1. *Draw and explain the block diagram of directional static overcurrent relay.*

6.14 Static Differential Relay

AU : Dec.-09

A differential relay is the relay which operates when the phasor difference of two or more similar electrical quantities exceed a predetermined value.

In static differential relay, two similar quantities either voltages or currents are compared. The comparator measures the vector difference between the two similar input signals. The rectifier bridge type comparator is generally used in the static differential relay. The block diagram is shown in the Fig. 6.14.1.

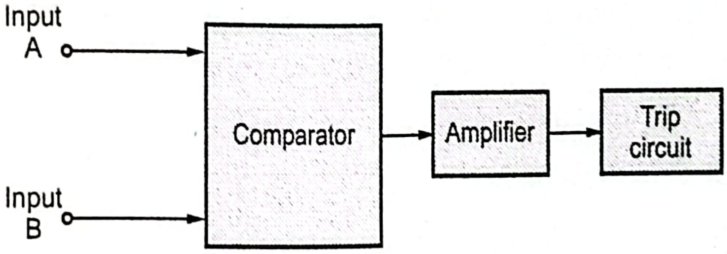


Fig. 6.14.1 Static differential relay

In normal conditions, the two quantities balance each other and the comparator output is zero and the relay is inoperative.

For any internal fault conditions, the comparator senses the phase difference between the two quantities and produces the output. This is amplified and given to the trip circuit which operates the relay.

This scheme is used for protection of the generators and transformers against any type of internal fault.

The various advantages of static differential relay over electromagnetic differential relay are, highly sensitive, compact, very fast in operation, low power consumption, less burden on input CTs and inrush current proof characteristics.

The basic static differential relay scheme is shown in the Fig. 6.14.2.

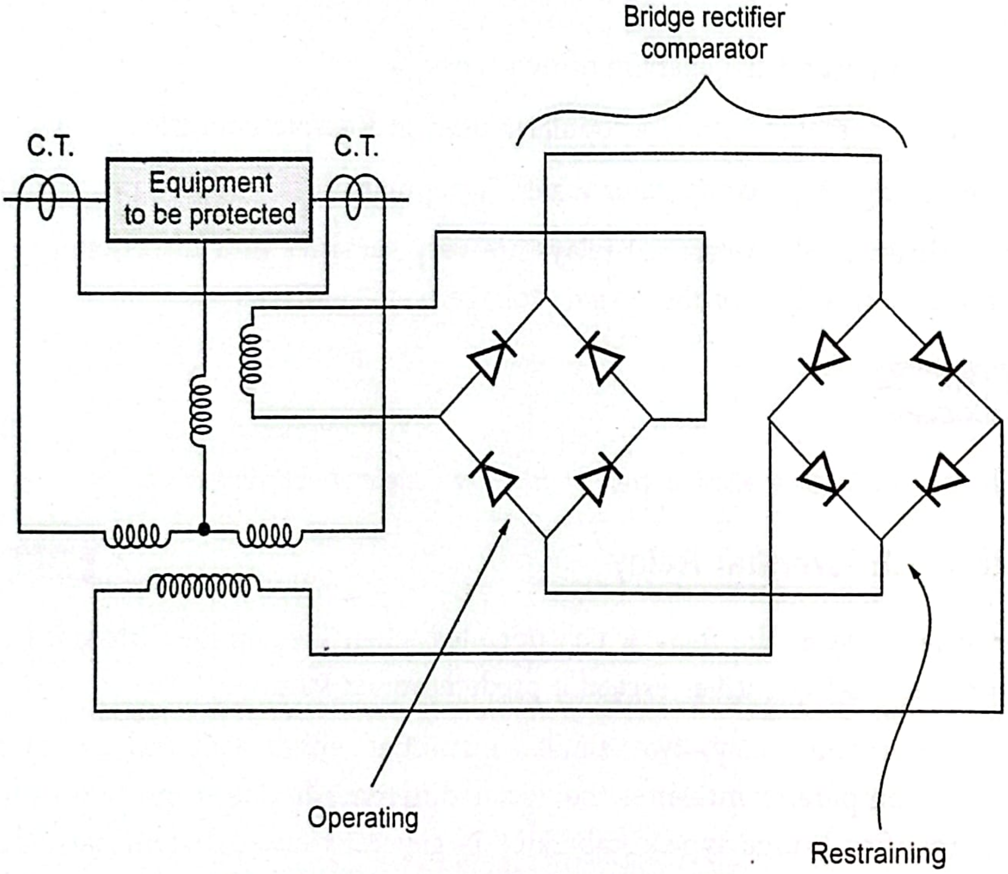


Fig. 6.14.2 Static differential relay scheme

Let n_o and n_r be the number of turns of operating and restraining coils respectively. Then the relay operates when,

$$K_1 n_o I_o > K_2 n_r I_r + K'$$

where K_1 and K_2 are design constants while K' is the spring control torque.

Review Question

1. *Discuss the static differential relay. State its advantages over electromagnetic differential relay.*

AU : Dec.-09, Marks 6

6.15 Static Distance Relay

AU : May-19

In the distance relay, the operation is dependent on the ratio of the voltage and current, which is expressed interms of an impedance. The relay operates when the ratio V/I i.e. impedance is less than a predetermined value. The distance relays include impedance, reactance and admittance relays as discussed earlier. In static relays the comparison of voltage and current is achieved by electronic comparator circuits.

The basic block diagram of static distance relay is shown in the Fig. 6.15.1.

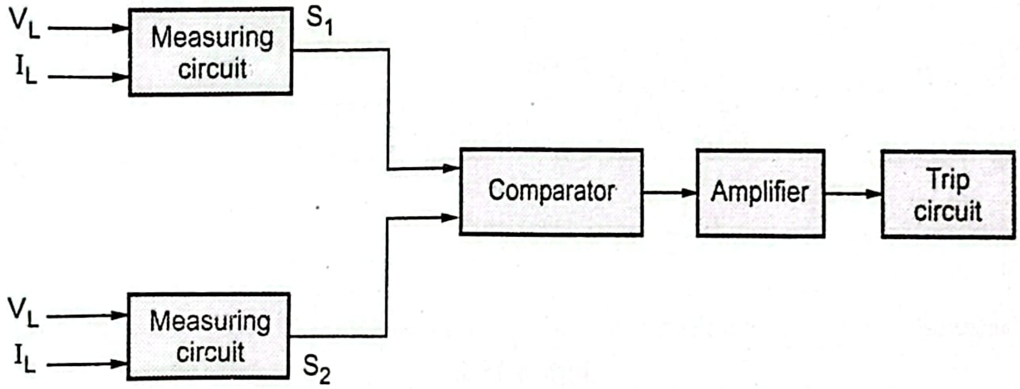


Fig. 6.15.1 Basic static distance relay scheme

The line voltage V_L and line current I_L are given as the inputs to the two measuring circuits. The circuits produce the outputs S_1 and S_2 depending upon their characteristics. Thus,

$$S_1 = K_1 V_L + K_2 I_L$$

$$S_2 = K_3 V_L + K_4 I_L$$

where K_1, K_2, K_3 and K_4 are to be selected according to the requirement of the characteristics.

Now depending upon whether the comparator is amplitude or phase comparator and the constants K_1 to K_4, the various characteristics of the distance relay can be obtained.

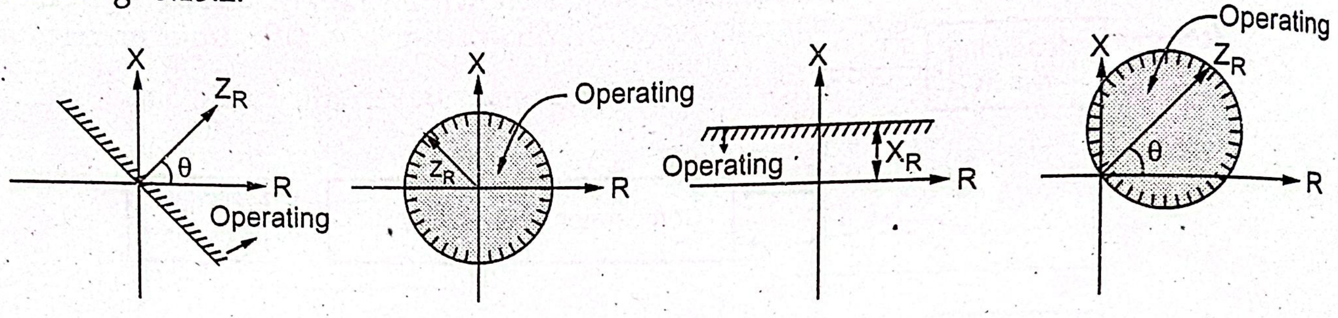
The various types of derived voltages S_1 and S_2 for amplitude and phase comparators to obtain particular characteristics are given in the Table 6.15.1.

Sr. No.	Amplitude comparator		Phase comparator		Distance relay scheme
	Operating	Restraining	Operating	Restraining	
1.	$\left\lvert I_L + \frac{V_L}{Z_R} \right\rvert$	$\left\lvert I_L - \frac{V_L}{Z_R} \right\rvert$	$I_L Z_R$	V_L	Directional
2.	$\lvert I_L \rvert$	$\frac{\lvert V_L \rvert}{\lvert Z_R \rvert}$	$I_L Z_R - V_L$	$I_L Z_R + V_L$	Impedance

3.	$\left\lvert I_L - \frac{V_L}{X_R} \right\rvert$	$\left\lvert \frac{V_L}{X_R} \right\rvert$	$I_L Z_R - V_L \sin\theta$	$I_L Z_R$	Reactance
4.	$\lvert I_L \rvert$	$\left\lvert I_L - \frac{V_L}{Z_R} \right\rvert$	$I_L Z_R - V_L$	V_L	Mho

Table 6.15.1

The characteristics of various schemes as obtained from above Table 6.15.1 are shown in the Fig. 6.15.2.



(a) Directional (b) Impedance (c) Reactance (d) Mho

Fig. 6.15.2

The static distance relays are used popularly for protection of medium and long transmission lines, parallel feeders and interconnected and T connected lines.

Review Question

1. *Explain the basic static distance relay scheme.* **AU : May-19, Marks 13**

6.16 Synthesis of Mho Relay using Static Comparator

AU : Dec.-16, May-22

The mho relay has a characteristics with a circle having diameter Z_R. This is the setting of the relay. It operates when the impedance seen by the relay falls within this circle. This is shown in the Fig. 6.16.1.

The relay is located at point A. Let the impedance seen by the relay be Z_{f1} indicated by point P. As it lies within the circle, the output of relay must be trip output.

Join the phasor PB which represents $(Z_R - Z_{f1})$ which leads the phasor $AP = Z_{f1}$ by angle θ_1.

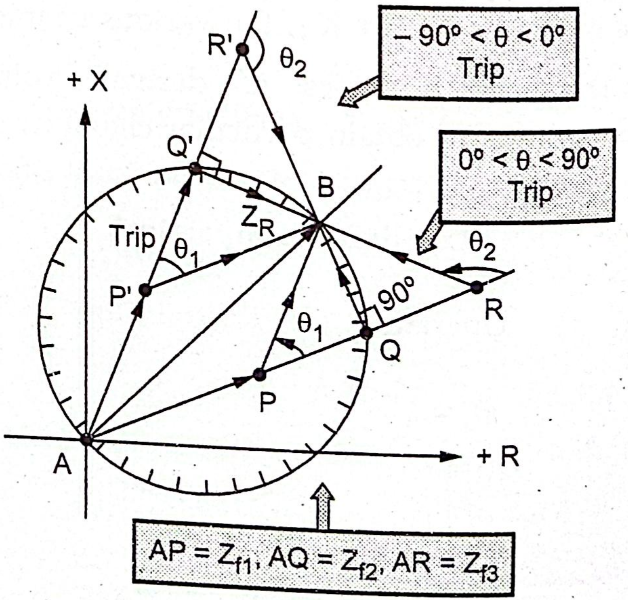


Fig. 6.16.1 Synthesis of mho relay

The angle θ_1 is less than 90°. As the fault location moves from P towards Q, the angle θ increases towards 90°. On the boundary at point Q, angle θ is exactly 90°. While if fault impedance lies outside the circle such as $AR = Z_{f3} > Z_R$ then θ is greater than 90° indicated as θ_2 and relay will not trip.

Hence,

$0° < \theta < 90° \rightarrow$ Trip, $\theta = 90° \rightarrow$ Threshold

$\theta > 90° \rightarrow$ Restrain is the trip law

Similarly if the fault impedance lies on the other side of $AB = Z_R$ i.e. at positions P', Q', R' as shown in the Fig. 6.16.1 then θ is negative. For points like P' where $AP' < Z_R$, θ is always greater than − 90°. At the point Q' on the boundary, $\theta = -90°$ while for all the points like R' where $AR' > Z_R$, θ is always less than − 90°.

Hence,

$-90° < \theta < 0° \rightarrow$ Trip, $\theta = -90° \rightarrow$ Threshold

$\theta > -90° \rightarrow$ Restrain is the trip law

The cosine static comparator is the one which operates when phase between the two inputs is between − 90° and + 90° hence synthesis of mho relay can be obtained using cosine phase comparator.

But static cosine comparator accepts only voltage signals as its inputs. Hence the impedances must be converted to voltages before giving them to comparator. This is possible by multiplying the phasors by current at relay location I_f.

The angle θ is angle between phasors OA and AP i.e. in general Z_f and $Z_R - Z_f$ where impedance seen by the relay upto general point P is Z_f. Multiply both by I_f, $Z_f I_f$ and $(Z_R - Z_f)\, I_f = Z_R I_f - Z_f I_f$. But the product $Z_f I_f$ is the voltage at relay location denoted as V_f. Hence the two inputs to the phase comparator are V_f and $(Z_R I_f - V_f)$

The synthesis of mho relay using cosine phase comparator is shown in the Fig. 6.16.2.

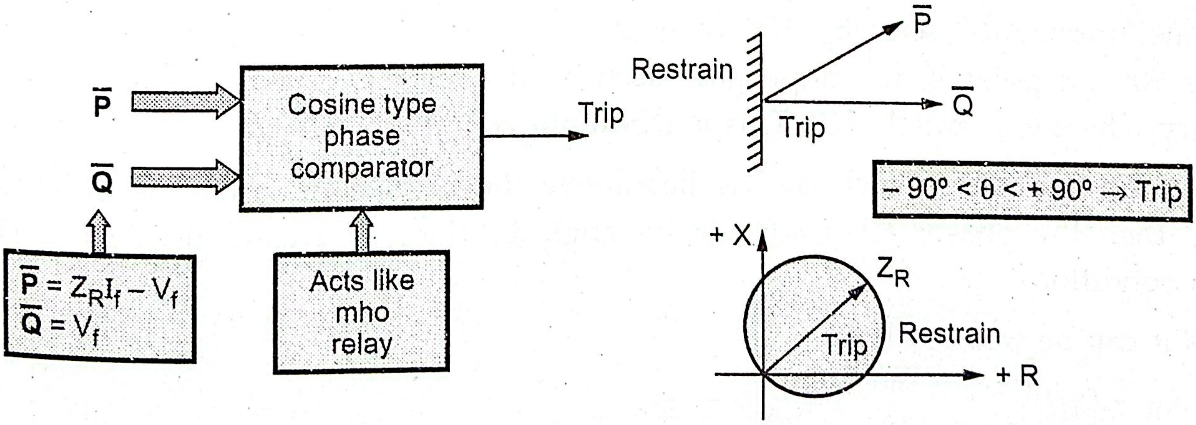


Fig. 6.16.2 Synthesis of mho relay using cosine phase comparator

Review Question

1. *Describe in detail the synthesis of a mho relay using static phase comparator.*

AU : Dec.-16, May-22, Marks 16

6.17 Synthesis of Reactance Relay using Static Comparators

AU : May-17,22

The reactance relay has a characteristics as a straight line parallel to the R-axis on R-X diagram at a distance of $|X_R|$ on X-axis. The setting of the relay is jX_R.

The impedance seen by the relay be Z_{f1}. The relay trips if this impedance lies below the straight line of $|X_R|$ as shown in the Fig. 6.17.1.

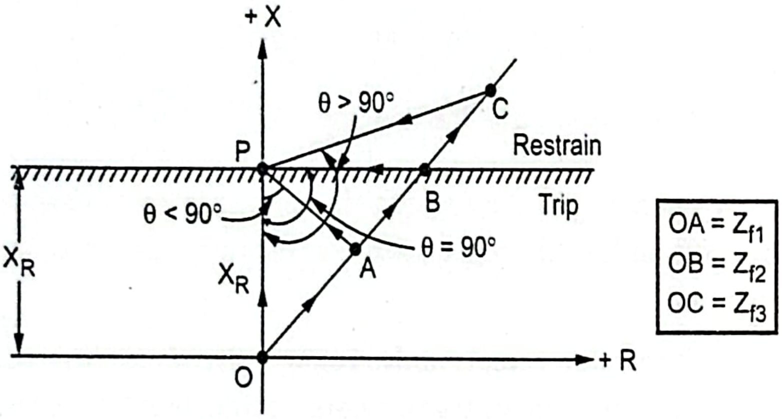


Fig. 6.17.1 Obtaining inputs for synthesis of reactance relay

The setting of the relay is OP = $|X_R|$

For impedance Z_{f1}, the relay trips as Z_{f1} lies at point A within the trip region, as shown.

Join the phasor AP which represents $|X_R - Z_{f1}|$. This phasor leads the phasor OP by angle θ which is less than 90°.

As the impedance seen by the relay moves from A to B, the angle θ increases towards 90°. At point B, the impedance seen by the relay is Z_{f2} and point B is on the boundary where θ is exactly 90°. This is **threshold** condition.

When the impedance such as Z_{f3} lies above the characteristic line as indicated by point C then the phasor CP leads OP by angle θ which is greater than 90°. This is **restrain** condition.

Thus it can be written that,

$$\angle \frac{|X_R - Z_{f1}|}{|X_R|} = \angle \text{OPA} < 90^\circ \Longrightarrow \text{Trip}$$

$$\angle \frac{|X_R - Z_{f2}|}{|X_R|} = \angle \text{ OPB} = 90° \Longrightarrow \text{Threshold}$$

$$\angle \frac{|X_R - Z_{f3}|}{|X_R|} = \angle \text{ OPC} > 90° \Longrightarrow \text{Restrain}$$

Hence,

$$\boxed{\text{If } \angle \frac{|X_R - Z_f|}{|X_R|} < 90° \rightarrow \text{Trip}} \quad \text{... Trip law}$$

Similarly if the fault impedance lies on the other side of OP i.e. to the left of jX_R phasor then it can be written that,

$$\angle \frac{|X_R - Z_{f1}|}{|X_R|} = \angle \text{ OPA} > -90° \Longrightarrow \text{Trip}$$

$$\angle \frac{|X_R - Z_{f2}|}{|X_R|} = \angle \text{ OPB} = 90° \Longrightarrow \text{Threshold}$$

$$\angle \frac{|X_R - Z_{f3}|}{|X_R|} = \angle \text{ OPC} < -90° \Longrightarrow \text{Restrain}$$

Hence,

$$\boxed{\text{If } \angle \frac{|X_R - Z_f|}{|X_R|} > -90° \rightarrow \text{Trip}} \quad \text{... Trip law}$$

Thus $(X_R - Z_{f1})$ and X_R are the two inputs to a cosine type comparator for synthesizing the reactance relay.

But static cosine comparator accepts only voltage signals as its inputs. Hence the impedances must be converted to voltages before giving them to comparator. This is possible by multiplying the phasors by current at relay location I_f.

The angle θ is between phasors OP and AP i.e. in general between X_R and $X_R - Z_f$. Multiplying both by I_f, the angle is between $X_R \, I_f$ and $(X_R - Z_f) I_f$. But the product $Z_f I_f$ is the voltage at relay location denoted as V_f.

Thus the two inputs to the comparater are,

$$\bar{P} = X_R I_f - V_f \text{ and } \bar{Q} = X_R I_f$$

The synthesis of reactance relay using consine phase comparator is shown in the Fig. 6.17.2.

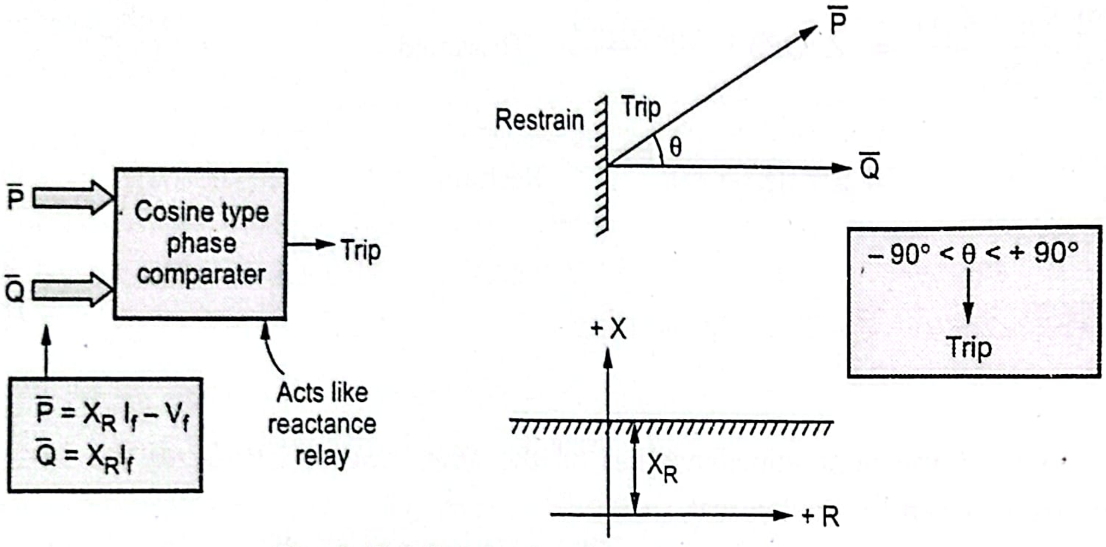

P̄
Q̄
Cosine type phase comparater
Trip
P̄ = X_R I_f − V_f
Q̄ = X_R I_f
Acts like reactance relay
P̄
Restrain
Trip
θ
Q̄
−90° < θ < + 90°
Trip
+X
X_R
+R

Fig. 6.17.2 Synthesis of reactance relay

Review Question

1. *Describe in detail, the synthesis of reactance relay using static phase comparator.*

AU : May-17,22, Marks 16

6.18 Synthesis of Impedance Relay

The synthesis of simple impedance relay is obtained using amplitude comparator. This is because the impedance relay characteristics is a circle of magnitude $|Z_R|$ and relay trips if actual $|Z_f|$ is less than $|Z_R|$.

The amplitude comparator has two inputs. The one is $|Z_R|$ and other is $|Z_f|$. But to have inputs as voltage signals, these signals are multiplied by the current at the fault point I_f. Thus the signals are,

$$\bar{P} = \text{Operating signal} = I_f |Z_R|$$

$$\bar{Q} = \text{Restraining signal} = I_f |Z_f| = V_f$$

But $I_f |Z_f|$ is the voltage at the fault point denoted as V_f hence $\bar{Q} = V_f$.

Thus the synthesis of simple impedance relay using amplitude comparator can be shown as in the Fig. 6.18.1.

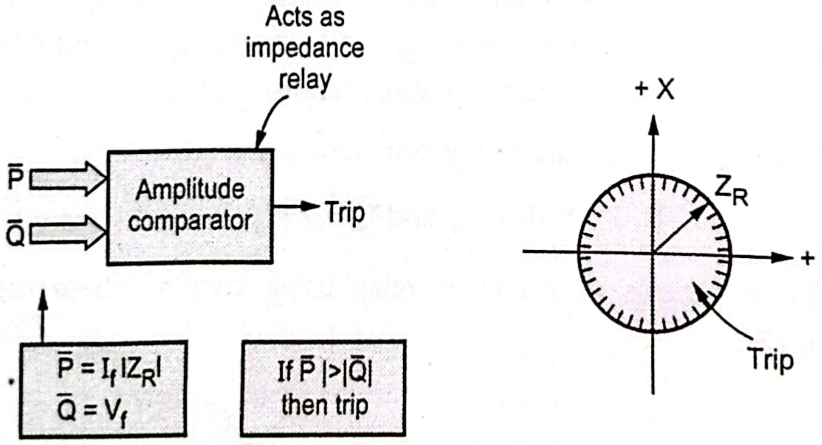

Acts as impedance relay
P̄
Q̄
Amplitude comparator
Trip
P̄ = I_f |Z_R|
Q̄ = V_f
If |P̄| > |Q̄| then trip
+X
Z_R
+R
Trip

Fig. 6.18.1 Synthesis of impedance relay

Review Question

1. *Discuss the synthesis of simple impedance relay.*

6.19 Block Diagram of Numerical Relay

AU : May-17,18, Dec.-22

A relay using digital device like microprocessor for decision making based on digital numbers representing instantaneous values of the signals is called **numerical relay, digital relay, microprocessor based relay** or **computer based relay.**

The Fig. 6.19.1 shows the block diagram of a numerical relay.

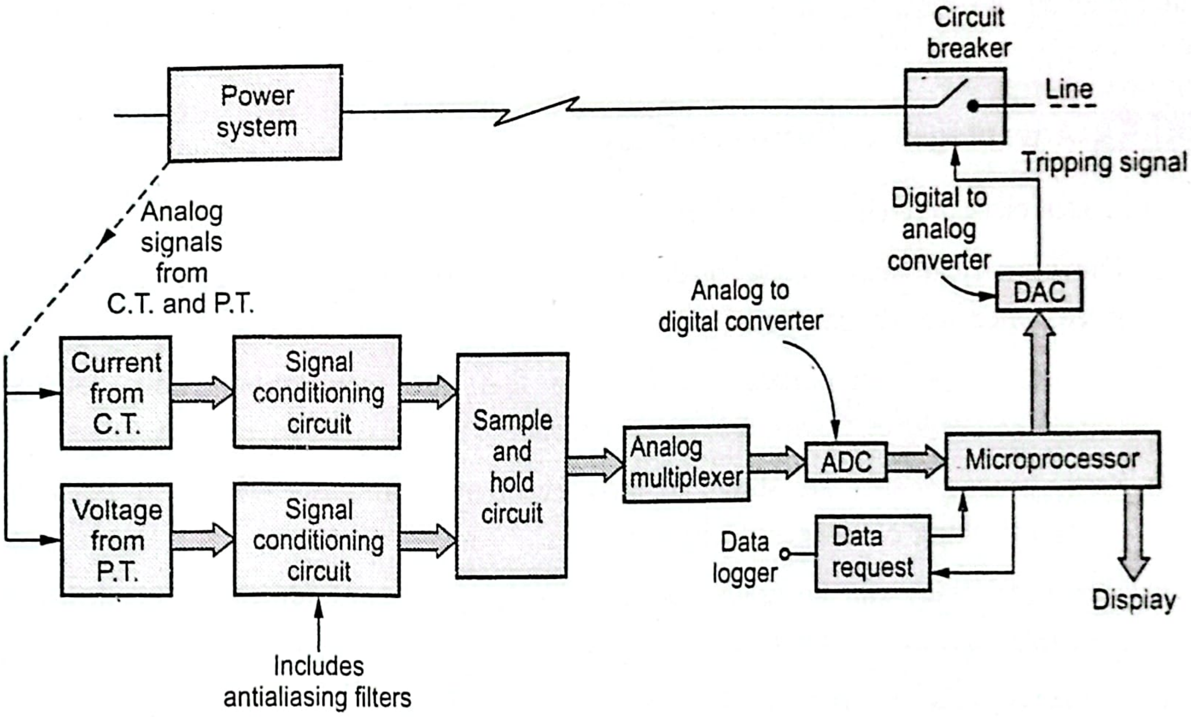

Circuit breaker
Line
Power system
Tripping signal
Digital to analog converter
DAC
Analog signals from C.T. and P.T.
Analog to digital converter
Current from C.T.
Signal conditioning circuit
Sample and hold circuit
Analog multiplexer
ADC
Microprocessor
Voltage from P.T.
Signal conditioning circuit
Data logger
Data request
Display
Includes antialiasing filters

Fig. 6.19.1 Block diagram of numerical relay

The voltage and current signals in the power system are brought down to suitable level using C.T. and P.T. These signals can not be converted to digital form. It is necessary to remove high frequency components which may appear as low frequency components. This is called aliasing which distorts the required signal.

Thus the signals from C.T. and P.T. are given to the antialiasing filters which are low pass filters. This removes unwanted frequency components.

The signals from signal conditioning circuits are sampled using sample and hold circuit. With the help of analog multiplexer and analog to digital converter (ADC), the equivalent digital form of analog input signal is achieved. The analog multiplexer gives the facility to accommodate a large number of input signals.

The digital output of ADC is given to microprocessor or microcontroller where it is stored in the memory. The signal is processed with the help of numerical relaying algorithm and accordingly trip decision is made.

The trip signal is digital signal hence converted to analog using digital to analog converter (DAC). This tripping analog signal is given to the trip coil of a relay.

The data logger captures the data and feeds it to the microprocessor when there is a request from the microprocessor. The information can be displayed with a proper display if required, by taking information from the microprocessor.

The numerical relay is programmable and periodically it performs self diagnostic test and produces an alarm signal if there is mismatch in the normal routine. This improves its reliability.

6.19.1 Advantages of Numerical Relay

1) It uses electronic circuits for functioning and hence is compact in size.
2) The numerical relay can be made multifunctional with suitable modifications in software or with slight modification in hardware.
3) It uses fewer components resulting in less inter connections and reduced component failures. Hence it is more reliable.
4) Relay characteristics are stored in memory of microprocessor. Hence it provides better matching of protection characteristics.
5) Numerical relay can be easily interfaced with digital communication equipments (like fibre optical communication).
6) Numerical relay imposes less burden on CTs and PTs.
7) It has high pick up ratio and greater sensitivity.
8) Tripping time of 1/2 cycle or less can be achieved with the use of numerical relay.
9) It has least resetting time.
10) It can provide data history for future reference.
11) One unit can perform relaying of several systems.
12) Very economical for large power systems.
13) Useful for centrally co-ordinated back up protection.

6.19.2 Limitations of Numerical Relay

1) The microprocessor unit needs to be properly shielded as gets affected by external interferences and environment.
2) Proper care of earthing must be taken.

3) If it is multifunctional, then failure of one element affects all the systems.
4) It has risk of hacking.
5) The relay can be faster but of no use if circuit breaker operation is not as fast as relay.

Review Questions

1. *Draw and explain the block diagram of a numerical relay.* **AU : May-17, Marks 16**
2. *State the advantages and limitations of a numerical relay.* **AU : May-18, Marks 8**
3. *Discuss about the block diagram of numerical relay with neat sketch with its advantages and limitations.* **AU : Dec.-22, Marks 13**

6.20 Numerical Overcurrent Protection

AU : Dec.-16

The Fig. 6.20.1 shows the block diagram of numerical overcurrent protection scheme.

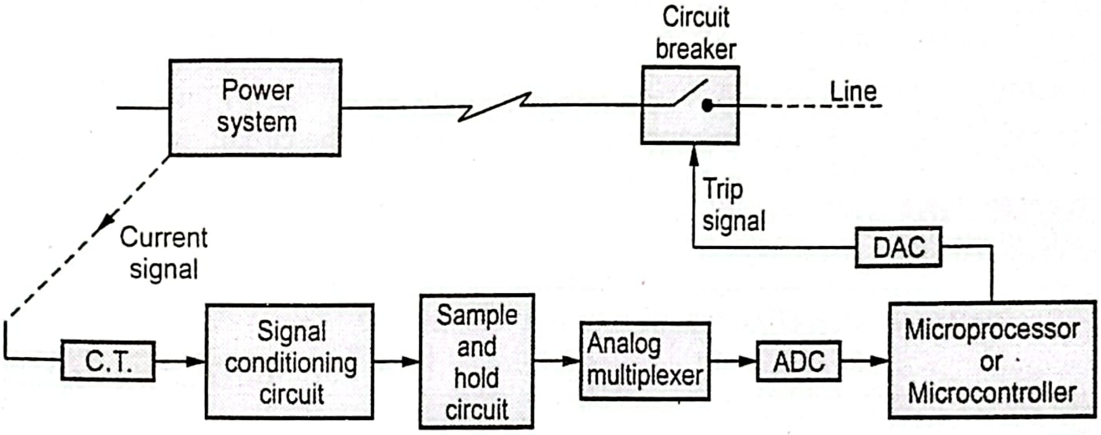


Fig. 6.20.1 Numerical overcurrent protection

The current signal from the power system is brought to the desired level using C.T. The signal conditioning circuit converts this signal to proportional voltage signal by removing high frequency components. This is possible by using antialiasing filter.

This signal is converted to equivalent digital form using sample and hold circuit, analog multiplexer and ADC in cascade.

The digital voltage signal is then applied to the microprocessor or microcontroller. It is processed by numerical filtering algorithm.

The microprocessor stores the settings such as type of characteristics to be implemented, the pick up value of current, time setting multiplier, the delay if required etc.

The numerical algorithm calculates the r.m.s value of the fundamental component of the fault current. The d.c. offset is filtered using Fourier transform. Then the r.m.s. value of fundamental component of current is compared with the stored pick up value of current to calculate the plug setting multiplier. For this PSM, microprocessor computes the time of operation depending on the characteristics to be implemented.

The time is calculated using the expression,

$$t = \frac{k}{I^n - 1}$$

Where k and n take values as per the characteristics to be implemented.

No.	Characteristics to be implemented	k	n
1.	IDMT	0.14	0.02
2.	Very inverse	13.5	1
3.	Extremely inverse	80	2
4.	Definite - time	As per design	0

According to the computation result, microprocessor generates tripping signal. This is given to the trip coil after passing through DAC, to operate the circuit breaker.

Review Question

1. *Explain the operation of numerical overcurrent relay with the help of a block diagram.*

AU : Dec.-16, Marks 8

6.21 Numerical Differential Protection of Transformer

AU : Dec.-16, May-22

In the percentage differential protection of transformers, the operating coil of the relay carries a differential current which is proportional to the phasor difference $(I_1 - I_2)$ while the restraining coil carries the current proportional to $\frac{(I_1 - I_2)}{2}$.

The operating characteristics of percentage differential relay is shown in the Fig. 6.21.1.

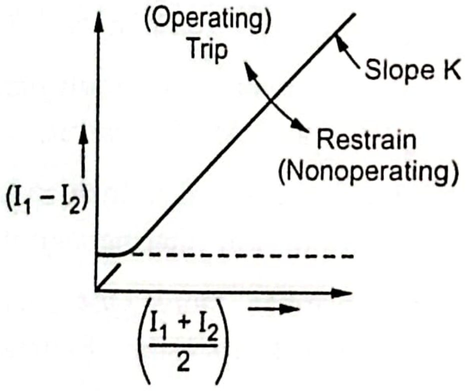


Fig. 6.21.1

The trip law is,

$$(I_1 - I_2) \geq K\left(\frac{I_1 + I_2}{2}\right) \quad \dots (6.21.1)$$

Where K is the bias i.e. slope of the characteristics whose value is between 0.15 to 0.6.

The Fig. 6.21.2 shows the block diagram of numerical differential protection scheme used for the transformers.

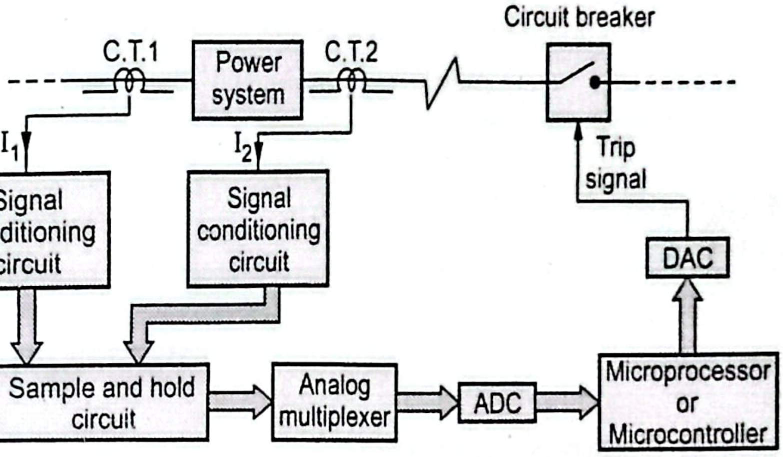


Fig. 6.21.2 Numerical differential protection of transformer

The currents I_1 and I_2 are sensed by the two C.T.s and given to the signal conditioning circuits. The circuit converts the signals to the proportional voltage signals and extracts the signals proportional to the fundamental frequency components of the currents.

The output of signal conditioning circuits is given to the sample and hold circuit. With the help of sample and hold circuit, analog multiplexer and ADC, the equivalent digital signals proportional to I_1 and I_2 are obtained. These digital signals are given to the microprocessor where they are stored in the memory.

The numerical algorithm is used to check the necessary condition given by equation (6.21.1). If it is satisfied, the microprocessor generates a tripping signal. This signal is given to the trip coil through digital to analog converter. This operates the circuit breaker.

Important consideration in such a relay is the possibility of false tripping of a relay because of magnetizing inrush current and over excitation inrush current. This condition should be restrained. This possibility is mainly because high second harmonic components present in magnetizing inrush current and high third and fifth harmonic components present in over excitation inrush current. Third harmonic is taken care of due to delta connection but second harmonic must be less than 15 % of the fundamental component while fifth harmonic must be less than 8 % of the fundamental component. This relay should not operate if second harmonic is more than 15 % and the fifth harmonic is more than 8 % of the fundamental. Hence along with the trip law, the following blocking or restraining law is also confirmed by the numerical algorithm.

$$\left.\begin{array}{l}(I_1-I_2)_2 \geq 0.15 \ (I_1-I_2)_1 \\ (I_1-I_2)_5 \geq 0.08 \ (I_1-I_2)_1\end{array}\right\} \text{Blocking law} \quad \ldots (6.21.2)$$

where $(I_1-I_2)_2$ is second harmonic, $(I_1-I_2)_5$ is fifth harmonic and $(I_1-I_2)_1$ is the fundamental component.

The numerical filtering algorithm is used to extract fundamental, second and fifth harmonic components. The trip decision is based on the conditions given by the equations (6.21.1) and (6.21.2).

Review Question

1. *Discuss the operation of numerical differential protection scheme used for the transformers.*

AU : Dec.-16, May-22, Marks 8

6.22 Numerical Distance protection

The distance protection is widely used for the protection of transmission lines. The distance protection is based on the measurement of the impendance at the relay location.

A protection scheme which uses numerical distance relays for the transmission line protection is called numerical distance protection scheme.

The Fig. 6.22.1 shows the block diagram of numerical distance protection of transmission line.

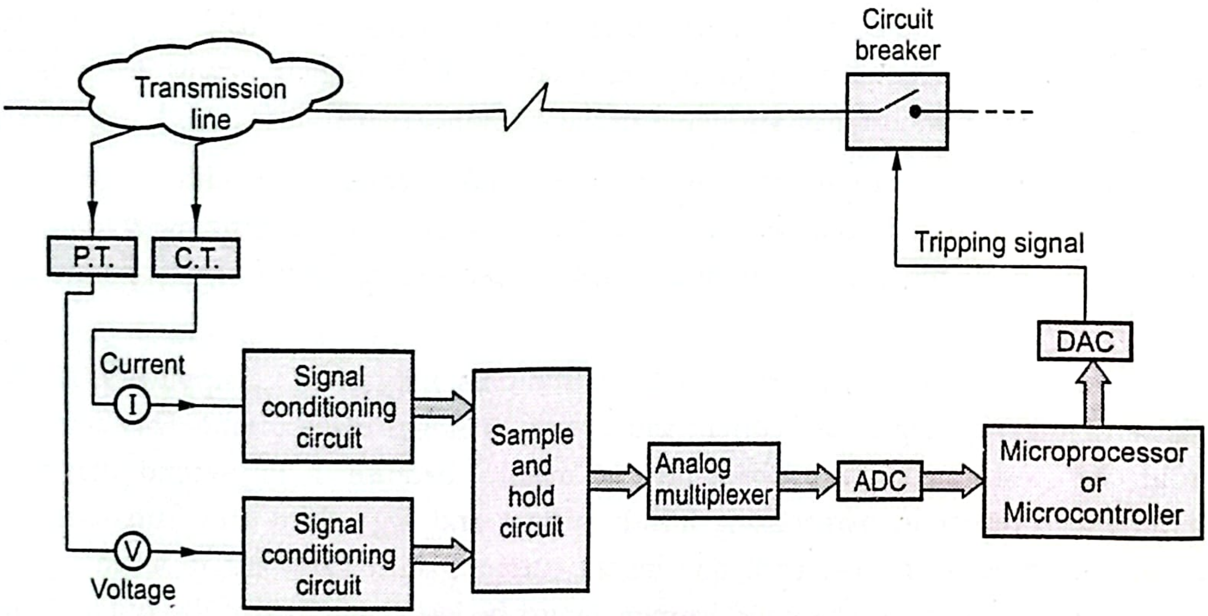

Circuit breaker
Transmission line
P.T.
C.T.
Tripping signal
DAC
Current
I
Signal conditioning circuit
Sample and hold circuit
Analog multiplexer
ADC
Microprocessor or Microcontroller
V
Voltage
Signal conditioning circuit

Fig. 6.22.1 Numerical distance protection

For measuring impedance or component of impedance, the analog voltage and current signals are measured using C.T and P.T. These analog voltage and current signals contain d.c. transient offset and harmonic frequency components in addition to the fundamental frequency component. The signal conditioning circuit seperates the fundamental frequency voltage and current components which is essential to calculate impedance.

Then the signals are converted to equivalent digital form, passing them through sample and hold circuit, analog multiplexer and analog to digital converter. These digital signals are stored in the memory of microprocessor.

Using numerical filtering algorithm, fundamental Fourier sine and cosine coefficients for both voltage and current are calculated. These are used to express the voltage and current in the complex form as,

$$V = V_x + j\,V_y \quad \text{and} \quad I = I_x + j\,I_y$$

The resistance and reactive (R and X) components of the impedance of the line as seen by the relay can then be computed as,

$$R = \frac{V_x\,I_x + V_y\,I_y}{I_x^2 + I_y^2}, \quad X = \frac{V_y\,I_x - V_x\,I_y}{I_x^2 + I_y^2}$$

The program is used to calculate R and X values, using above equations. The algorithm includes the information about the characteristics to be implemented as impedance relay, reactance relay or mho relay.

Using the calculated values, the microprocessor takes the decision depending on whether the fault point lies within the defined protective zone of the relay or not.

The tripping signal is then given to digital to analog converter and is applied to a trip coil of a circuit breaker.

Review Question

1. *Explain the operation of a numerical distance protection scheme used for the transmission line protection.*

6.23 Two Marks Questions with Answers

Q.1 What are static relays ? **AU : Dec.-17, May-19**

Ans. : The relays which do not use moving parts and use the solid electronic components such as diodes, transistors etc. are called **static relays.**

Q.2 List out the basic elements of a static relay. **AU : May-18**

Ans. : 1. Input element which is rectifier or a mixing circuit such as op-amp adder etc.

2. Measuring element which is single input, double input or multi-input device

3. Critical measuring function which is sort of on-off controller

4. Output element which is an amplifier
5. Feed element which provides d.c. supply to the various elements.

Q.3 State the main functions of noncritical repeat function in a static relay.

Ans. : 1. To produce final tripping signal to a circuit breaker.

2. To produce signals to perform supplementary functions such as alarming.
3. To act as intermediate switching stage in a complex protection scheme.

Q.4 State the requirements of critical function device in a static relay.

Ans. : 1. High accuracy. 2. Long term consistency.

3. Fast and reliable operation. 4. High controllable reset ratio.

Q.5 State the merits of static relays. (Refer section 6.4) **AU : Dec.-10, 13, 14, 18, May-14**

Q.6 Compare static and electromagnetic relays. (Refer section 6.3) **AU : Dec.- 06, 11**

Q.7 List out the applications of static relays. **AU : Dec.-12, 16**

Ans. : 1. Protection of generators and transformers against any type of internal fault.

2. Protection of medium and long transmission lines.
3. Protection of parallel feeders and interconnected lines.
4. Protection of prime movers of generators such as steam and gas turbines, diesel engines etc.
5. Protection of large generators against overloading.

Q.8 Draw the block diagram of a static relay. **AU : Dec.-08**

Ans. :

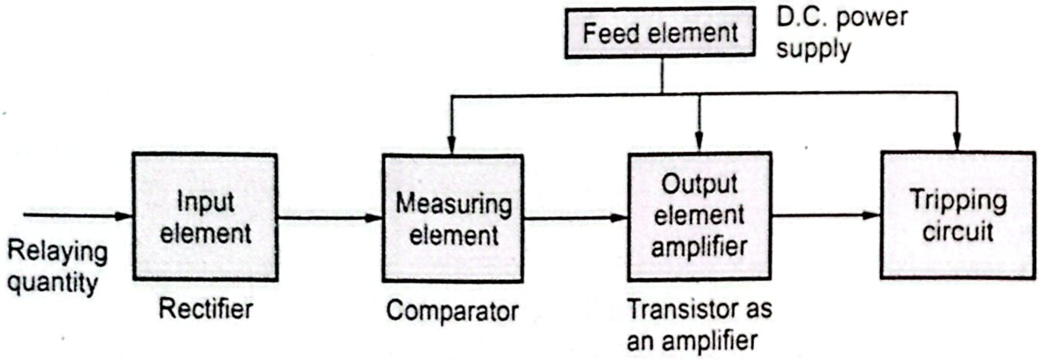


Fig. 6.23.1 Block diagram of a static relay

Q.9 List out the semiconductor devices used in static relays.

Ans. : 1. Semiconductor diodes 2. Transistors 3. Unijunction transistor

4. Thyristor family such as SCR, triacs, diacs etc. 5. Logic circuits

6. Filter circuits 7. Multivibrators 8. Time delay circuits

9. Level detectors 10. Analog circuits using op-amp

Q.10 Draw the block diagram of numerical relay. (Refer Fig. 6.19.1 from section 6.19)

AU : May-22

Q.11 State the advantages of numerical protection. (Refer section 6.19.1) **AU : May-18**

Q.12 State the limitations of numerical relay. (Refer section 6.19.2)

Q.13 State the difference between conventional relay and numerical relay.

AU : Dec.-16

Ans. : A relay which detects the fault and is responsible to energize the trip circuit using mechanical parts and springs is called conventional relay.

A relay using digital device like microprocessor for decision making based on digital numbers, representing instantaneous values of the signals is called **numerical relay, digital relay, microprocessor based relay** or **computer based relay.**

Q.14 Define sampling theorem. **AU : May-17**

Ans. : The sampling theorem states that, if x(t) is strictly band limited signal with Fourier spectrum $X(j\omega) = 0$ for $|\omega| > \omega_m$ then x(t) can be recovered without any loss of information from its sample signal $x(n) = x(nT_s)$, if the sampling frequency ω_s is greater than twice of the maximum frequency ω_m of x(t) i.e. $\omega_s > 2\omega_m$. The minimum sampling frequency is called **Nyquist sampling rate.**

Q.15 Write about numerical transformer differential protection. (Refer section 6.21)

AU : May-17

Q.16 What is phase comparator ? **AU : Dec.-17**

Ans. : A phase comparator detects the phase angle between the two inputs. If the phase angle is lying within specified limits, it produces the output.

Q.17 List the electronic circuits commonly used in static relays. **AU : Dec.-18**

Ans. : The electronic circuits and devices used in static relays are semiconductor diodes, transistors, unijunction transistors, thyristor family such as SCR, triac, diac, logic circuits, filter circuits, multivibrators, time delay circuits, level detectors and analog circuits.

Q.18 List the merits of numerical relays. **AU : May-19**

Ans. :

1) It uses electronic circuits for functioning and hence is compact in size.
2) The numerical relay can be made multifunctional with suitable modifications in software or with slight modification in hardware.
3) It uses fewer components resulting in less inter connections and reduced component failures. Hence it is more reliable.
4) Relay characteristics are stored in memory of microprocessor. Hence it provides better matching of protection characteristics.

5) Numerical relay can be easily interfaced with digital communication equipments (like fibre optical communication).

6) Numerical relay imposes less burden on CTs and PTs.

7) One unit can perform relaying of several systems.

8) Very economical for large power systems.

Q.19 What are the limitations of a static relay ? **AU : Dec.-22**

Ans. : The limitations of static relays are,

1. The characteristics of electronic components such as transistors, diodes etc. are temperature dependent. Hence relay characteristics vary with temperature and ageing.
2. The reliability is unpredictable as it depends on a large number of small components and their electrical connections.
3. These relays have low short time overload capacity compared to electromagnetic relays.
4. Additional d.c. supply is required for various transistor circuits.
5. Susceptable to the voltage fluctuations and transients.
6. Less robust compared to electromagnetic relays.

Q.20 List the types of static relays. **AU : Dec.-22**

Ans. : The various types of static relays are,

i) Rectifier bridge relays
ii) Transistor relays
iii) Hall effect relays
iv) Gauss effect relays
v) Magnetic amplifier relays (Transductor)
vi) Electronic relays.

Q.21 What is the difference between numerical relay and static relay ? **AU : May-22**

Ans. : The relays which do not use moving parts and use the solid state electronic components such as diodes, transistors etc. are called static relays.

The relays using digital device like microprocessor for decision making based on digital numbers representing instantaneous values of the signals are called numerical relays.

6.24 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *How will you synthesize a mho relay using static phase comparator ?* **[Section 6.16] [16]**

Q.2 *Explain the numerical over current protection and numerical transformer differential protection.* **[Sections 6.20 and 6.21]** **[16]**

May-17

Q.3 *Explain the block diagram of numerical relay with necessary diagram.* **[Section 6.19]** **[16]**

Q.4 *With a neat sketch discuss in detail about the synthesis of reactance relay using phase comparator.* **[Section 6.17]** **[16]**

Dec.-17

Q.5 *Explain with neat block diagram the operation of static relay and list the advantages and disadvantages.* **[Sections 6.2 and 6.4]** **[16]**

Q.6 *Describe the operation of static over current relay with neat diagram.* **[Section 6.12]** **[16]**

May-18

Q.7 *Describe the construction, working principle and operation of static over current relay.* **[Section 6.12]** **[16]**

Q.8 *Compare static relays with electromagnetic relays.* **[Section 6.3]** **[8]**

Q.9 *Explain the advantages of numerical relays.* **[Section 6.19.1]** **[8]**

Dec.-18

Q.10 *Discuss in detail, the integrating type and instantaneous type static amplitude comparators. Illustrate your answer with appropriate circuits and waveforms.* **[Section 6.6]** **[13]**

Q.11 *How static overcurrent relays are different from electromechanical overcurrent relays ? Explain how the operation of instantaneous overcurrent relay is achieved using electronic circuits.* **[Sections 6.3 and 6.12.2]** **[13]**

May-19

Q.12 *Draw the schematic block diagram of a static over current relay and explain the operation.* **[Section 6.12]** **[13]**

Q.13 *Explain the operation of distance protection of transmission lines using static comparators with neat diagram.* **[Section 6.15]** **[13]**

(Regulation 2017)

May-22

Q.14 *Explain with a neat diagram transformer differential protection for the numerical relay.* **[Section 6.21]** **[13]**

Q.15 *Enumerate the synthesis of various relays using static comparators.* **[Sections 6.16 and 6.17]** **[13]**

Q.16 *Explain the operation of static relay with a neat block diagram and discuss its advantages and disadvantages.* **[Sections 6.2 and 6.4]** **[15]**

Dec.-22

Q.17 *Discuss about the block diagram of numerical relay with neat sketch with its advantages and limitations.* **[Section 6.19]** **[13]**

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UNIT V

7

Theory of Circuit Interruption

Syllabus

Physics of arcing phenomenon and arc interruption - DC and AC circuit breaking - Re-striking voltage and recovery voltage - Rate of rise of recovery voltage - Current chopping - Interruption of capacitive current - resistance switching.

Contents

7.1	*Introduction*		
7.2	*Formation of an Arc*	**Dec.-06,11, May-07,**	*Marks 10*
7.3	*D.C. Circuit Breaking*	**May-06,07,14,19,** **Dec.-07,10,**	*Marks 8*
7.4	*A.C. Circuit Breaking*		
7.5	*Short Circuit in R-L Series Circuit*		
7.6	*Current Interruption in A.C. Circuit Breakers*	**May-11, Dec.-13**	*Marks 8*
7.7	*Transient Recovery Voltage*		
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7.9	*Recovery Voltage*		
7.10	*Single Frequency Transient*		
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7.12	*Derivation of Rate of Rise of TRV*	**May-04,05,07,08,12,15,** **Dec.-04,06,08,11,13,14,16**	*Marks 16*
7.13	*Interruption of Capacitive Currents*	**May-04,05,08,11,12,14,15,17,19** **Dec.-13,16,**	*Marks 8*
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7.15	*Resistance Switching*	**Dec.-04,06,07,11,12,15,17,18,** **May-05,13,18,**	*Marks 16*
7.16	*Arc Extinction*	**Dec.-06,07,08,10,11,** **May-13,**	*Marks 10*
7.17	*Ionization of Gases*		
7.18	*Deionization*		
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7.20	*High Resistance Arc Interruption Methods*	**May-14**	*Marks 8*
7.21	*Low Resistance or Zero Point Extinction*		
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7.23	*Auto Reclosing*		
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7.1 Introduction

The different circuits of a power system viz transmission lines, distributors, generating stations etc. are required to be operated under both normal and abnormal conditions. Whenever any fault occurs somewhere in the system, it must be immediately detected and the faulty part must be disconnected from the remaining healthy system. This is necessary since it ensures less damage to the faulted apparatus and the fault is not spread into the system. Also quick recovery of fault results in less interruption of service to the consumers.

Previously the function of switching on and off of the power system elements was accomplished with the help of switch and fuse which is placed in series with the circuit. But it suffers some difficulties such as replacement of fuse takes a long time. So supply to the consumers will be restored after long time. The another limitation is that it will not be able to interrupt successfully the heavy fault currents. Due to these disadvantages the use of switch and fuse unit is restricted to the low voltage and small capacity circuits where frequent operations are not performed.

With the development in power system the transmission lines and various equipments operate at very high voltages carrying large currents. The switch and fuse arrangement explained earlier will fail to serve the desired function in high capacity circuits. The use of circuit breakers can facilitate the opening and closing of heavy electric circuits smoothly and efficiently. **A circuit breaker can make or break a circuit either manually or automatically under no load, full load or short circuit conditions.** Thus it forms important element in any protective scheme.

Any circuit breaker essentially consists of fixed contact and moving contact. Under abnormal conditions or whenever the circuit breaker is operated then the internal mechanism makes the moving contact to move away from the fixed contact. Whenever contacts are separated from each other the circuit is not breaked immediately as heavy arc is drawn between the contacts which will continue for some time. The resistance of this arc is high which causes large power loss in the process. Also the components of circuit breaker are under heavy mechanical and electromagnetic stresses.

Review Question

1. *Define a circuit breaker. Describe its operation in brief.*

7.2 Formation of an Arc

AU : Dec.-06,11, May-07

Now let's see the formation of an arc. Under faulty conditions heavy current flows through the contacts of the circuit breaker before they are opened. As soon as the contacts start separating, the area of contact decreases which will increase the current density and consequently rise in the temperature. The medium between the contacts of circuit breaker may be air or oil. The heat which is produced in the medium is sufficient enough to ionize air or oil which will act as conductor. Thus an arc is struck between the contacts. The p.d. between the contacts is sufficient to maintain the arc. So long as the arc is remaining between the contacts the circuit is said to be uninterrupted.

The current flowing between the contacts depends on the arc resistance. With increase in arc resistance the current flowing will be smaller. The arc resistance depends on following factors,

a) **Degree of ionization :** If there are less number of ionized particles between the contacts then the arc resistance increases.

b) **Length of arc :** The arc resistance is a function of length of arc which is nothing but separation between the contacts. More the length, more is the arc resistance.

c) **Cross - section of arc :** If the area of cross-section of the arc is less then arc resistance is large.

7.2.1 Initiation of Arc

There must be some electrons for initiation of an arc when fault occurs circuit breaker contacts start separating from each other and the electrons are emitted which are produced by following methods.

i) By high voltage gradient at the cathode, resulting in field emission.

ii) By increase of temperature, resulting in thermionic emission.

7.2.1.1 By High Voltage Gradient

As the moving contacts start separating form each other, the area of contact and pressure between the separating contacts decreases. A high fault current causes potential drop (of the order of 10^6 V/cm) between the contacts which will remove the electrons from cathode surface. This process is called **field emission.**

7.2.1.2 By Increase of Temperature

With the separation of contacts there is decrease in contact area which will increase the current density and consequently the temperature of the surface as seen before, which will cause emission of electrons which is called **thermal electron emission.**

In most of the circuit breakers the contacts are made up of copper which is having less thermionic emission.

7.2.2 Maintenance of an Arc

In the previous section we have seen the initiation of the arc by field emission and thermionic emission. The electrons while travelling towards anode collide with another electrons to dislodge them and thus the arc is maintained. The ionizing is facilated by,

i) High temperature of the medium around the contacts due to high current densities. Thus the kinetic energy gained by moving electrons is increased.

ii) The increase in kinetic energy of moving electrons due to the voltage gradient which dislodge more electrons from neutral molecules.

iii) The separation of contacts of circuit breaker increases the length of path which will increase number of neutral molecules. This will decrease the density of gas which will increase free path movement of the electrons.

7.2.3 Arc Extinction

It is essential that arc should be extinguished as early as possible. There are two methods of extinguishing the arc in circuit breakers which are namely,

a) High resistance method

b) Low resistance or current zero method

7.2.3.1 High Resistance Method

In high resistance method the arc resistance is increased with time. This will reduce the current to such a value which will be insufficient to maintain the arc. Thus the current is interrupted and the arc is extinguished. This method is employed in only d.c. circuit breakers. The resistance of the arc may be increased by lengthening the arc, cooling the arc, reducing the cross-section of the arc and splitting the arc. These methods will be discussed in detail later in this chapter.

7.2.3.2 Low Resistance Method

The low resistance or current zero method is employed for arc extinction in a.c. circuits. In this method arc resistance is kept low until current zero where extinction of arc takes place naturally and is prevented from restriking. This method is employed in many of the modern a.c. circuit breakers.

Review Questions

1. *How arc is initiated and sustained when the circuit breaker contacts break ?*

AU : Dec.-06, May-07, Marks 8, Dec.-11, Marks 6

2. *Explain in detail various methods of arc extinction.*

AU : May-07, Marks 8, Dec.-11, Marks 10,

7.3 D.C. Circuit Breaking

AU : May-06,07,14,19, Dec.-07,10

The breaking in case of d.c. circuits can be explained as follows. For this, we will consider a circuit which will consist of generator with voltage E, resistance R, inductor L and the circuit breaker as shown in the Fig. 7.3.1 (a).

The voltage-current relationship can be represented as shown in the Fig. 7.3.1 (b).

From the Fig. 7.3.1 (b), it could be seen that curve AB represents the voltage E - iR, i is nothing but current at any instant. The curve XY represents the voltage-current characteristics of the arc for decreasing currents.

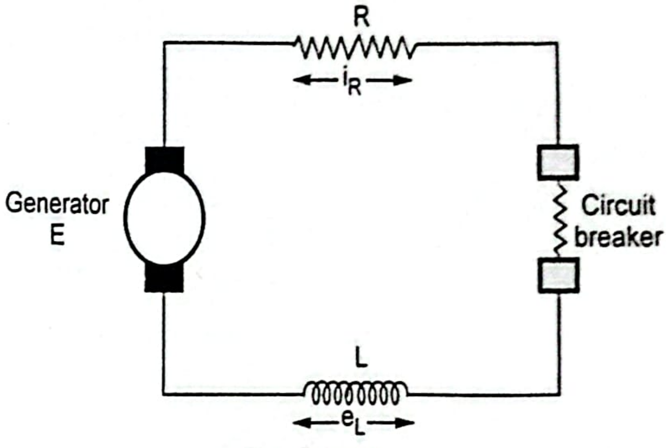


Fig. 7.3.1 (a)

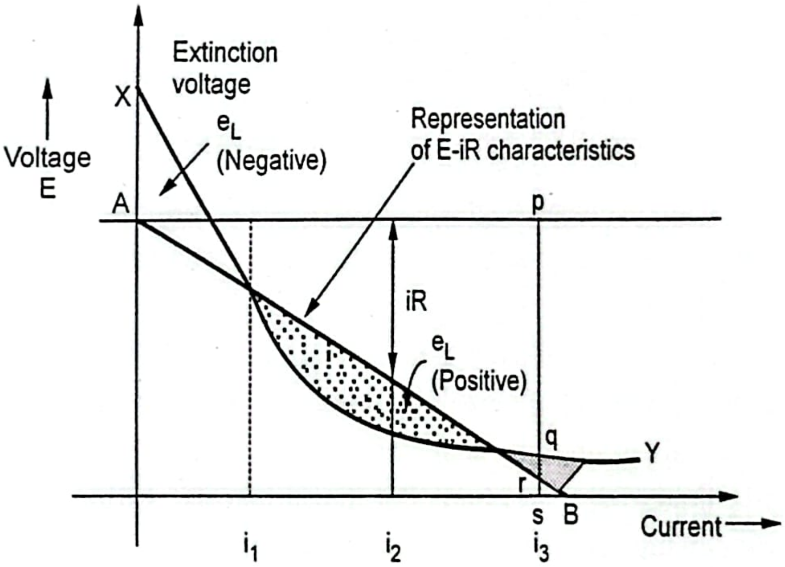


Fig. 7.3.1 (b) Voltage-Current relationship

When the circuit breaker starts opening it carries the load current $I = \frac{E}{R}$. In the graph shown the current is shown to be reduced to i_1, i_2 and i_3 respectively. Section pr represents voltage drop i_3R whereas qs represents arc voltage which is greater than available voltage. The arc becomes unstable and the difference in voltage is supplied by inductance L across which the voltage is $e_L = L\frac{di}{dt}$. For decreasing values of currents this voltage is negative and according to Lenz's law it tries to maintain the arc.

The voltage across inductance L is seen to be positive in the region of currents i_1 and i_2 since the arc characteristics lies below the curve AB. The arc current in this region tries to increase so interruption of current is not possible in this region. Afterwards the arc is lengthened with increase in contact separation which will raise the arc voltage above the curve AB.

The operation in case of d.c. circuit breakers is said to be ideal if the characteristics of the arc voltage are above the curve AB even in the region of currents i_1 and i_2. This is shown in the Fig. 7.3.2.

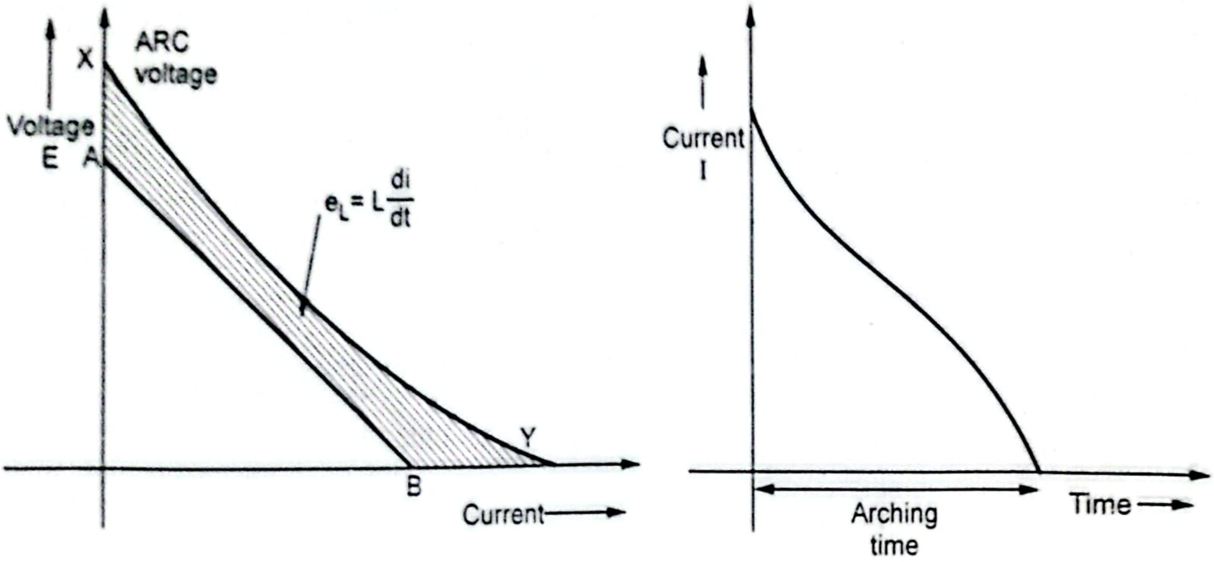


Fig. 7.3.2 Arc voltage characteristics

It can be seen that arc voltage is greater than E – iR and the balance between the voltages is supplied by the voltage across the inductance e_L which is proportional to rate of change of current $\frac{di}{dt}$.

Thus the function of the circuit breaker is to raise the arc characteristics without affecting its stability. This is done by reducing the arcing time which is the time from contact separation to final extinction of arc. But it will increase extinction voltage. Hence compromise between arcing time and arc extinction voltage is made.

Review Questions

1. *Write a note on d.c. circuit breaking.*
2. *Explain the principle of D.C. circuit breaking.*

AU : May-06,19, Marks 6, May-07, 14, Dec.-07, 10, Marks 8

7.4 A.C. Circuit Breaking

There is a difference between breaking in case of d.c. and a.c. circuits. In a.c. circuits the current passes through zero twice in one complete cycle. When the currents are reduced to zero the breakers are operated to cut-off the current. This will avoid the striking of the arc. But this conditions is difficult to achieve and very much expensive.

The restriking of arc when current is interrupted is dependent on the voltage between the contact gap at that instant which will inturn depend on power factor. Higher the power factor, lesser is the voltage appearing across the gap than its peak value.

Now before studying the actual current interruption in a.c. circuits we will see some theory which will help us in understanding this concept.

7.5 Short Circuit in R-L Series Circuit

Consider a series R-L circuit as shown in the Fig. 7.5.1 in which switch S is suddenly closed at time t = 0.

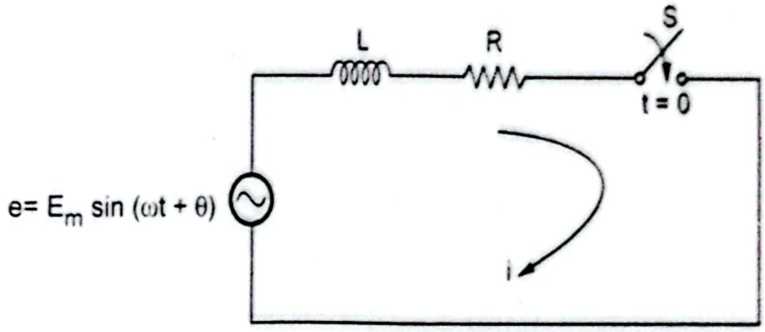


Fig. 7.5.1 R-L series circuit

Applying KVL to above circuit,

$$L\frac{di}{dt} + Ri = e \quad \text{i.e.} \quad L\frac{di}{dt} + Ri = E_m \sin(\omega t + \theta) \qquad \dots (7.5.1)$$

This equation can be solved to get the expression for current i. This is a non-homogeneous differential equation whose solution consists of two parts viz complementary solution and particular solution i.e. $i = i_C + i_P$.

Complementary solution : To get the complementary solution we will consider the auxiliary equation which is obtained by equating right hand side of above equation to zero.

$$L\frac{di}{dt} + Ri = 0 \qquad \dots (7.5.2)$$

Separating the variables, $\frac{di}{i} = -\frac{R}{L}dt$

Integrating and solving, $\log i = -\frac{R}{L}t + K$ where K is constant of integration

Considering $K = \log_e A$

$\therefore \quad \log_e i = \log_e e^{(-R/L)t} + \log_e A$

$\therefore \quad \log_e i = \log_e A e^{(-R/L)t}$

Taking antilog on both sides, $i = A e^{(-R/L)t}$

This is complementary solution. This component of current is seen to be exponentially decaying component and called D.C. component. The constant of integration A depends on initial conditions which may be zero, positive or negative.

$$\therefore \quad i_C = A e^{(-R/L)t} \qquad \dots (7.5.3)$$

Particular solution : For particular solution we will take a trial solution as,

$$i = C\cos(\omega t+\theta)+D\sin(\omega t+\theta) \qquad \dots (7.5.4)$$

Taking $\frac{di}{dt}$ and $\frac{d^2i}{dt^2}$ of above equation,

$$\frac{di}{dt} = -C\omega\sin(\omega t+\theta)+D\omega\cos(\omega t+\theta)$$

$$\frac{d^2i}{dt^2} = -C\omega^2\cos(\omega t+\theta)-D\omega^2\sin(\omega t+\theta)$$

Putting this value in equation (7.5.1) and equating like coefficients,

$$C = -E_m\frac{\omega L}{R^2+\omega^2L^2} \quad \text{and} \quad D = E_m\frac{R}{R^2+\omega^2L^2}$$

Substituting these values of C and D in the trial solution we get,

$$i = -E_m\frac{\omega L}{R^2+\omega^2L^2}\cos(\omega t+\theta)+E_m\frac{R}{R^2+\omega^2L^2}\sin(\omega t+\theta) \dots (7.5.5)$$

If ϕ is the impedance angle then,

$$\therefore \quad \tan\phi = \frac{\omega L}{R}, \quad \therefore \sin\phi = \frac{\omega L}{\sqrt{R^2+\omega^2L^2}}, \quad \therefore \cos\phi = \frac{R}{\sqrt{R^2+\omega^2L^2}}$$

$$i = \frac{-E_m}{\sqrt{R^2+\omega^2L^2}}\sin\phi\cos(\omega t+\theta)+\frac{E_m}{\sqrt{R^2+\omega^2L^2}}\cos\phi\sin(\omega t+\theta)$$

$$= \frac{E_m}{\sqrt{R^2+\omega^2L^2}}[\sin(\omega t+\theta)\cos\phi-\cos(\omega t+\theta)\sin\phi]$$

$$= \frac{E_m}{\sqrt{R^2+\omega^2L^2}}\sin(\omega t+\theta-\phi)$$

$$\therefore \quad i_P = \frac{E_m}{\sqrt{R^2+\omega^2L^2}}\sin(\omega t+\theta-\phi) \qquad \dots (7.5.6)$$

The particular solution given by above equation is **sinusoidal** and is called **a.c. component.**

Complete solution : The total current i is given by,

$$i = i_C+i_P = A\,e^{-(R/L)t}+\frac{E_m}{\sqrt{R^2+\omega^2L^2}}\sin(\omega t+\theta-\phi) \qquad \dots (7.5.7)$$

To find the value of A let us put the initial conditions. At t = 0, i = 0. If R is assumed to be very small compared to $\omega^2 L^2$;

$$\sqrt{R^2+\omega^2L^2} \approx \omega L \text{ and } \phi = \tan^{-1}\frac{\omega L}{R} \approx 90°$$

Case i) : If switch is closed at e = 0

$$t = 0; \quad e = 0 \qquad \therefore \quad \theta = 0$$

Also $\quad i = 0$ at $t = 0$.

$$\therefore \quad 0 = A + \frac{E_m}{\sqrt{R^2+\omega^2L^2}} \sin(-90°) \quad \text{i.e.} \quad A = \frac{E_m}{\sqrt{R^2+\omega^2L^2}} = \frac{E_m}{\omega L}$$

This is the maximum value of A.

The d.c. component is maximum when switch is closed at zero voltage.

Case ii) : If switch is closed at $e = E_{max}$

$$t = 0; \quad e = E_{max} \qquad \therefore \quad \theta = 90° = \pi / 2$$

$$\therefore \quad 0 = A + \frac{E_m}{\sqrt{R^2+\omega^2L^2}} \sin(90° - 90°)$$

$$A = 0$$

If switch is closed when $e = E_{max}$ then A = 0 i.e. d.c. component is zero.

Thus when the circuit consisting of R and L supplied with alternating voltage, is closed at t = 0, the resulting current consists of two components viz a.c. and d.c. components which are superimposed on each other. The d.c. component magnitude is decided by the voltage at the instant of switching. When switch is closed at voltage zero, the d.c. component is maximum whereas the d.c. component is zero when switch is closed at voltage maximum.

The analysis of three phase short circuit of an alternator is done by similar way as we have done the analysis of short circuit of series R-L circuit. The current flowing through the phases of alternator during short circuit has similar waveform to that of R-L circuit as shown previously if we neglect armature reaction and variation in the field current.

During the short circuit, the current flowing through alternator rises rapidly to a high value during first quarter cycle. The flux which is crossing the air gap is large during first couple of cycles.

The subtransient reactance denoted by X_d'' is defined as that reactance during first two or three cycles. This is very less and correspondingly short circuit current is large.

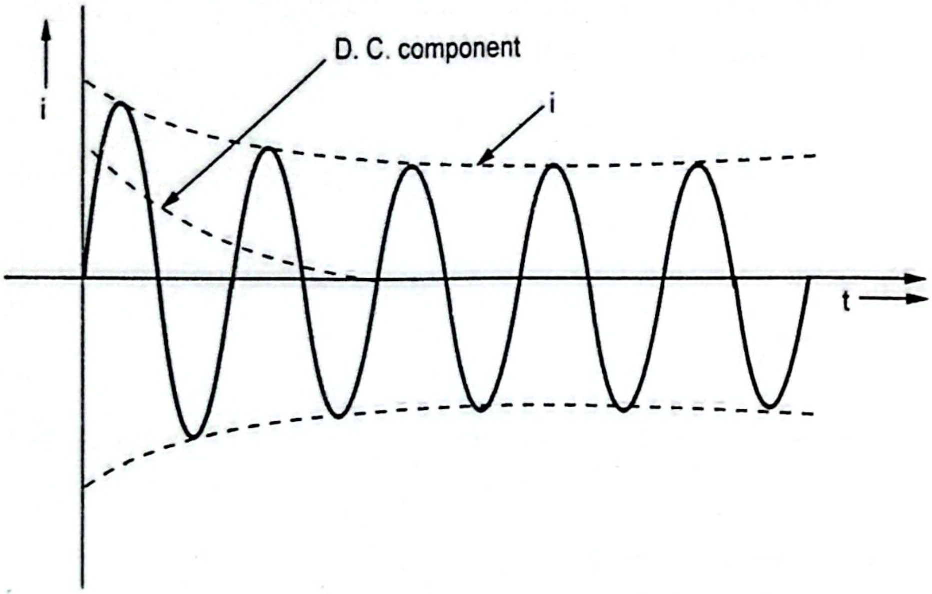


Fig. 7.5.2 Maximum d.c. component

After first few cycles which are coming under subtransient state the r.m.s. value of short circuit current goes on reducing but the decrease in current is not fast as in subtransient state. This state is called transient state and the corresponding reactance is called transient reactance denoted by X'_d. The circuit breaker contacts separate in this state.

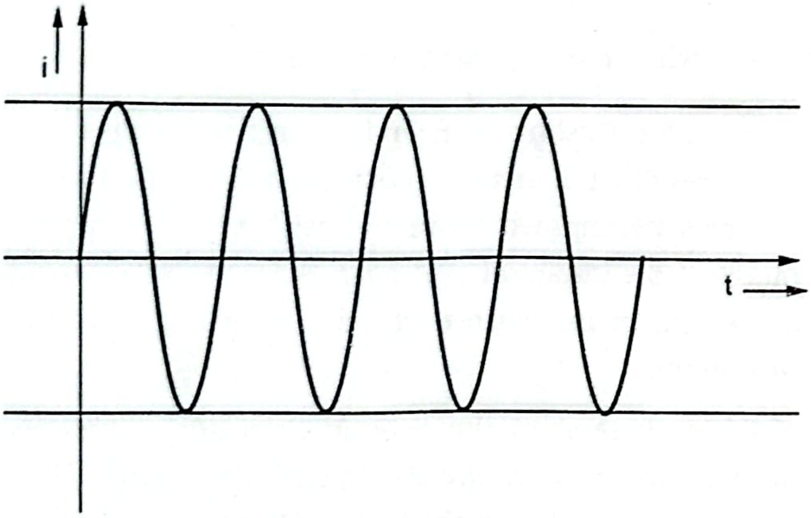


Fig. 7.5.3 No d.c. component

Finally the transients vanish and current will reach to steady sinusoidal state called steady state. The reactance in this state is called steady state reactance denoted by X_d.

The currents in the different phases are having different d.c. components. So their waveforms will be different. In the Fig. 7.5.4 the oscillogram of the current in the phase having zero d.c. component is shown.

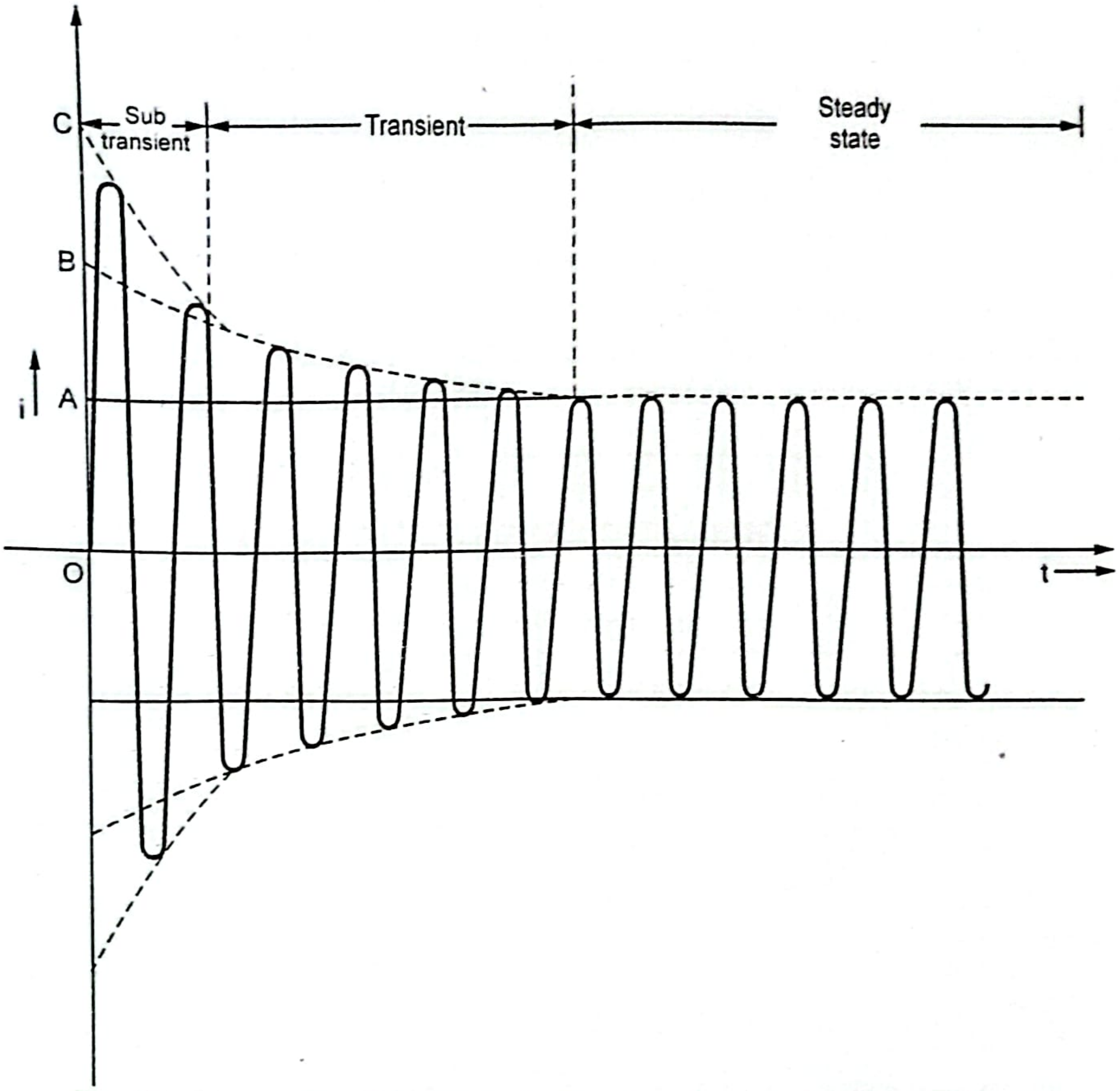


Fig. 7.5.4 Oscillogram of current in the phase having zero d.c. component

Review Question

1. *Draw an oscillogram of current with zero d.c. component.*

7.6 Current Interruption in A.C. Circuit Breakers

AU : May-11, Dec.-13

Now we will see how the current interruption takes place in a.c. circuit breakers. Generally the a.c. circuit breakers employ zero point interruption technique.

Let us consider an alternator on no load to which a circuit breaker is connected which is shown in the Fig. 7.6.1. The circuit breaker is in open position with its other side short circuited.

When the voltage of phase B w.r.t neutral is zero, the circuit breaker is closed. Under this condition the B phase current will have maximum d.c. component and its current waveform will be unsymmetrical about normal zero axis. This is shown in the Fig. 7.6.2.

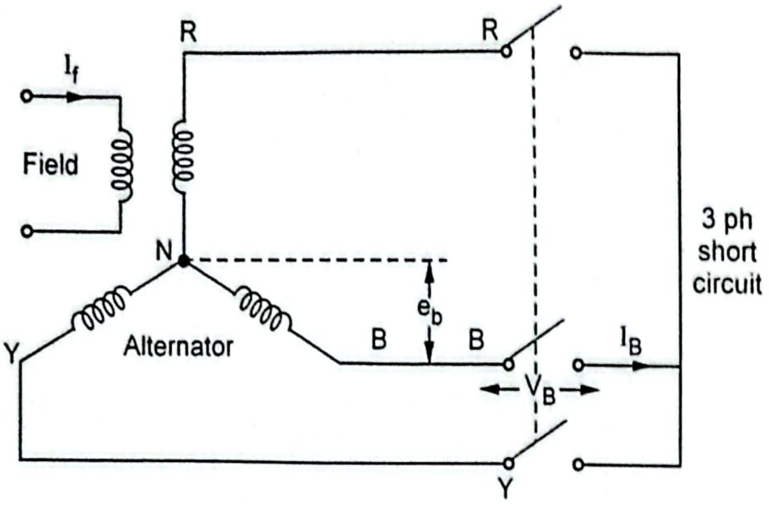

R
R
I_f
Field
3 ph
short
circuit
N
e_b
Y
Alternator
B
B
I_B
V_B
Y

Fig. 7.6.1 Sudden 3 phase short circuit of an alternator

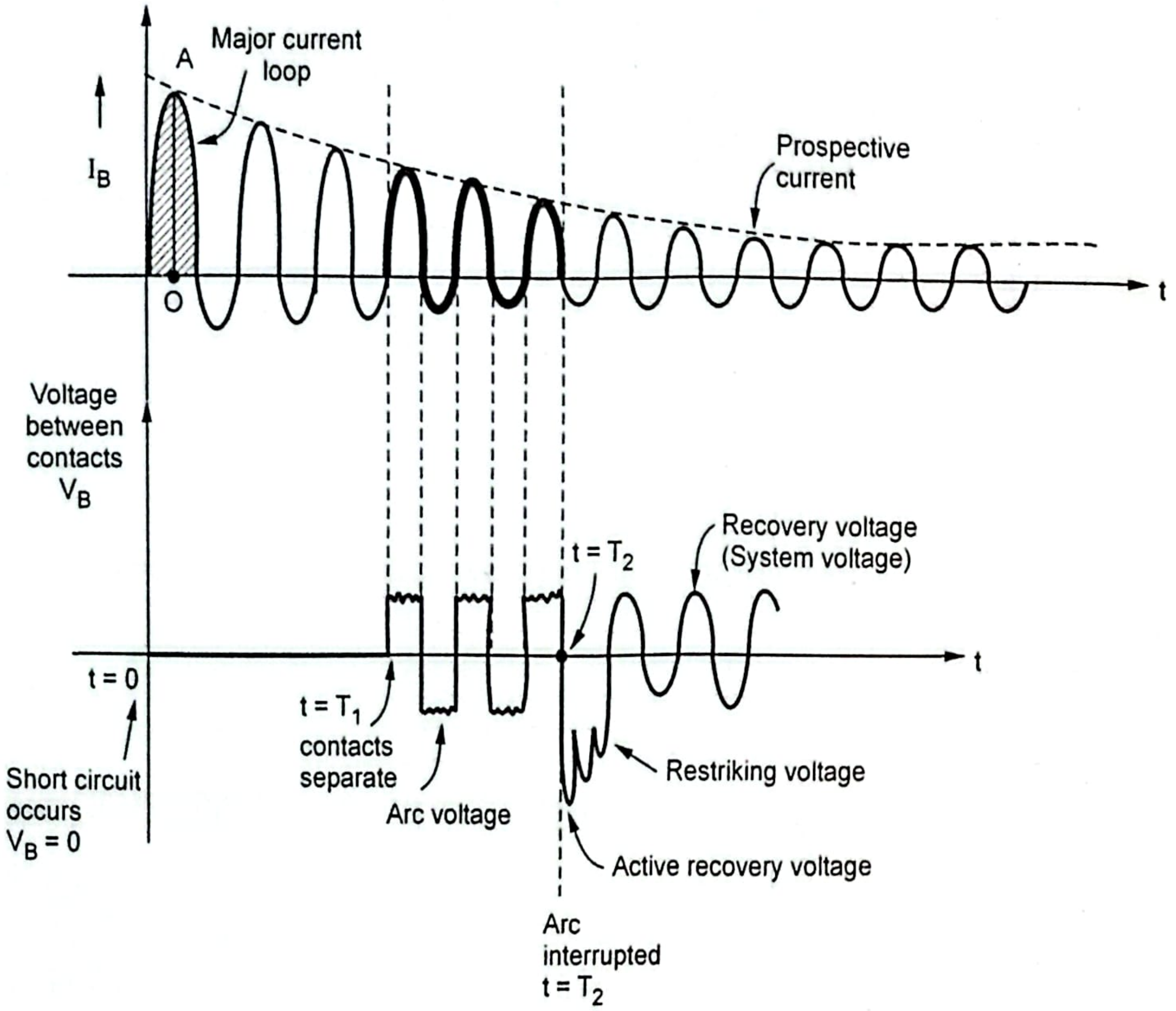

A
Major current
loop
I_B
Prospective
current
O
t
Voltage
between
contacts
V_B
t = T_2
Recovery voltage
(System voltage)
t
t = 0
Short circuit
occurs
V_B = 0
t = T_1
contacts
separate
Arc voltage
Restriking voltage
Active recovery voltage
Arc
interrupted
t = T_2

Fig. 7.6.2 Current and voltage waveforms during fault clearing

The current is zero before t = 0 as the alternator is on no load. The short circuit is applied at t = 0 and current increases to very high value (nearly 10 to 25 times full load current) during first quarter cycle. The peak of first current loop is shown by OA which is maximum instantaneous value of current during short circuit. This instantaneous peak value of first current loop is called **making current** which is expressed as kA peak. This loop is called **major current loop.**

Now the circuit breaker contacts will separate after few cycles which are taken by relay and other operating mechanism. At time say $t = T_1$ the contacts of circuit breaker separate. The r.m.s. value of short circuit current at that instant of contact separation is called **breaking current.**

As seen earlier an arc is struck between the contact when they start separating. The arc current varies sinusoidally for few cycles. At $t = T_2$ the arc is interrupted as the dielectric strength of arc space builds sufficiently. This will avoid the continuation of arc. Thus the arc will be extinguished.

The voltage waveform is shown in the Fig. 7.6.2. Before the instant $t = 0$, the contacts are closed so the voltage between them is zero. At the instant $t = T_1$, the contacts begin to separate and voltage across them starts increasing. This voltage is nothing but the drop across the arc. The current and the voltage across arc are in phase as the arc is resistive. Due to increased arc resistance the voltage across contacts increases in the next cycles. Finally at $t = T_2$ the arc is extinguished. A high frequency transient voltage appears across the contacts which is superimposed on power frequency voltage. This high frequency voltage tries to restrike the arc. Hence it is called Restriking Voltage or Transient Recovery Voltage. This is the voltage which appears across circuit breaker contact which is responsible for restriking of arc. The power frequency system voltage between the circuit breaker contacts after arc extinction is called recovery voltage. The prospective current shown in the waveform may be defined as the current that would flow in the circuit if circuit breakers were replaced by solid conductor.

Restriking voltage or Transient Recovery Voltage (TRV) : It is the transient voltage which appears across the breaker contacts at the instant of arc extinction.It is responsible for restriking of arc.

Recovery voltage : The power frequency r.m.s. voltage between the circuit breaker contacts after the transient oscillations die out and arc extinction has occurred in all the poles is called **recovery voltage.** This is nothing but the **system voltage.**

Active recovery voltage : It is the instantaneous recovery voltage at the instant of arc extinction.

Rate of Rise of Restriking Voltage (RRRV) : It is the rate at which the restriking voltage rises.

RRRV is important because if RRRV is smaller than the rate at which the dielectric between the contacts is developed then only arc gets extinguished.

Review Questions

1. *Explain current interruption in a.c. circuit breakers.*
2. *Explain the terms restriking voltage and recovery voltage.* **AU : May-11, Marks 6**
3. *Explain the operation of zero crossing in circuit breaker.* **AU : Dec.-13, Marks 8**

7.7 Transient Recovery Voltage

The transient recovery voltage has effect on the behaviour of circuit breaker. This voltage appears between the contacts immediately after final arc interruption. This causes high dielectric stress between the contacts. If this dielectric strength of the medium between the contacts does not build up faster than the rate of rise of the transient recovery voltage then the breakdown takes place which will cause restriking of arc. Thus it is very important that the dielectric strength of the contact space must build very rapidly that rate of rise of transient recovery voltage so that the interruption of current by the circuit breaker takes place successfully. The rate of rise of this transient voltage depends on the circuit parameters and the type of the switching duty involved. The rate of building up of the dielectric strength depends on the effective design of the interrupter and the circuit breaker.

If it is desired to break the capacitive currents while opening the capacitor banks, there may appear a high voltage across the contacts which can cause Reignition of the arc after initial arc extinction. Thus if contact space breaks down within a period of one fourth of a cycle from initial arc extinction the phenomenon is called Reignition. If moving contacts of circuit breakers move a very small distance from the fixed contacts then Reignition may occur without overvoltage. But the arc gets extinguished in the next current zero by which time moving contacts should be moved by sufficient distance from fixed contacts. Thus the Reignition is in a way not harmful as it will not lead to any overvoltage beyond permissible limits.

If the breakdown occurs after one fourth of a cycle, the phenomenon is called Restrike. In restriking, high voltage appear across the circuit breaker contacts during capacitive current breaking. In successive restrikes, voltage will go on increasing which may lead to damage of circuit breaker. Thus the circuit breakers used for capacitors should be free from Restrike i.e. they should have adequate rating.

Review Question

1. *What is restrike ?*

7.8 Effect of Different Parameters on Transient Recovery Voltage (TRV)

As seen from the previous section, after the final current, zero high frequency transient voltage appears across the circuit breaker poles which is superimposed on power frequency system voltage and tries to restrike the arc. This voltage may last for a few tens or hundreds of microseconds. If the shape of this TRV is seen on the oscilloscope then it can be seen that it may be oscillatory, non-oscillatory or a combination of two depending upon the characteristics of the circuit and the circuit breaker. The waveform is as shown in the Fig. 7.8.1.

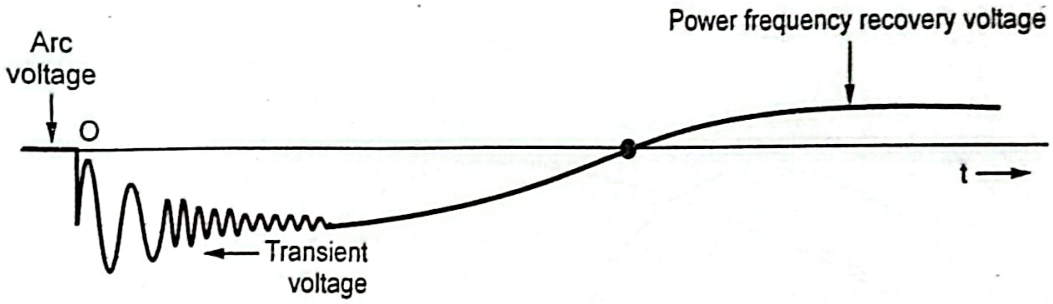


Fig. 7.8.1 Shape of transient recovery voltage

This voltage has a power frequency component and an oscillatory transient component. The oscillatory component is due to inductance and capacitance in the circuit. The power frequency component is due to the system voltage. This is shown in the Fig. 7.8.2.

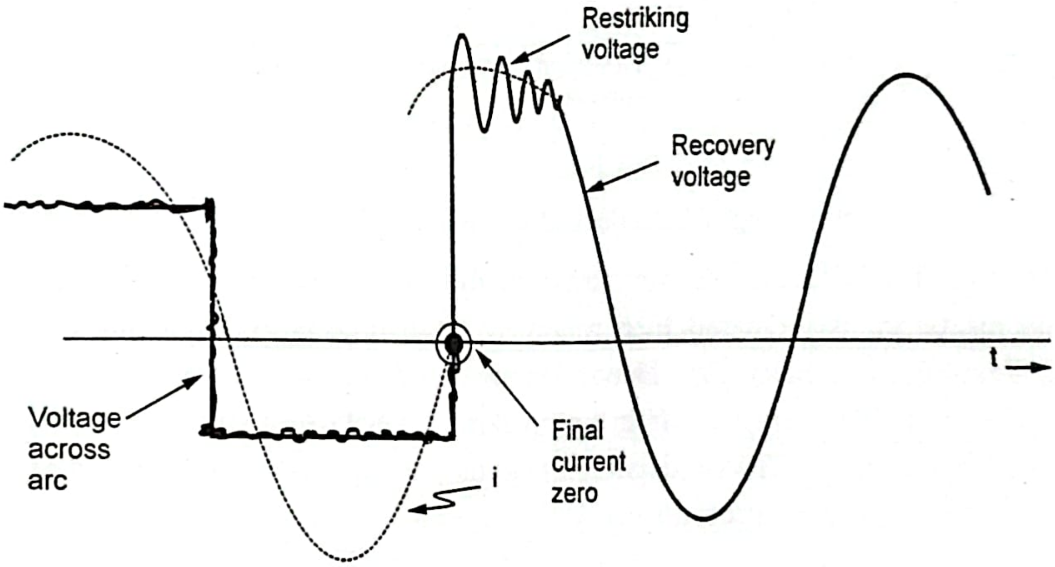


Fig. 7.8.2 Voltages after final current zero

The transient oscillatory component lasts for few microseconds after which power frequency voltage remains. The transient component has frequency given by,

$$f_n = \frac{1}{2\pi\sqrt{LC}} \text{ Hz}$$

where f_n = Frequency of transient recovery voltage

L = Equivalent inductance

C = Equivalent capacitance

7.8.1 Effect of Natural Frequency on TRV

With increase in the natural frequency the rate of rise of TRV at current zero increases. This is shown in the Fig. 7.8.3. The rate of rise of transient recovery voltage is represented by slopes of tangents to the three waveforms drawn at different frequencies.

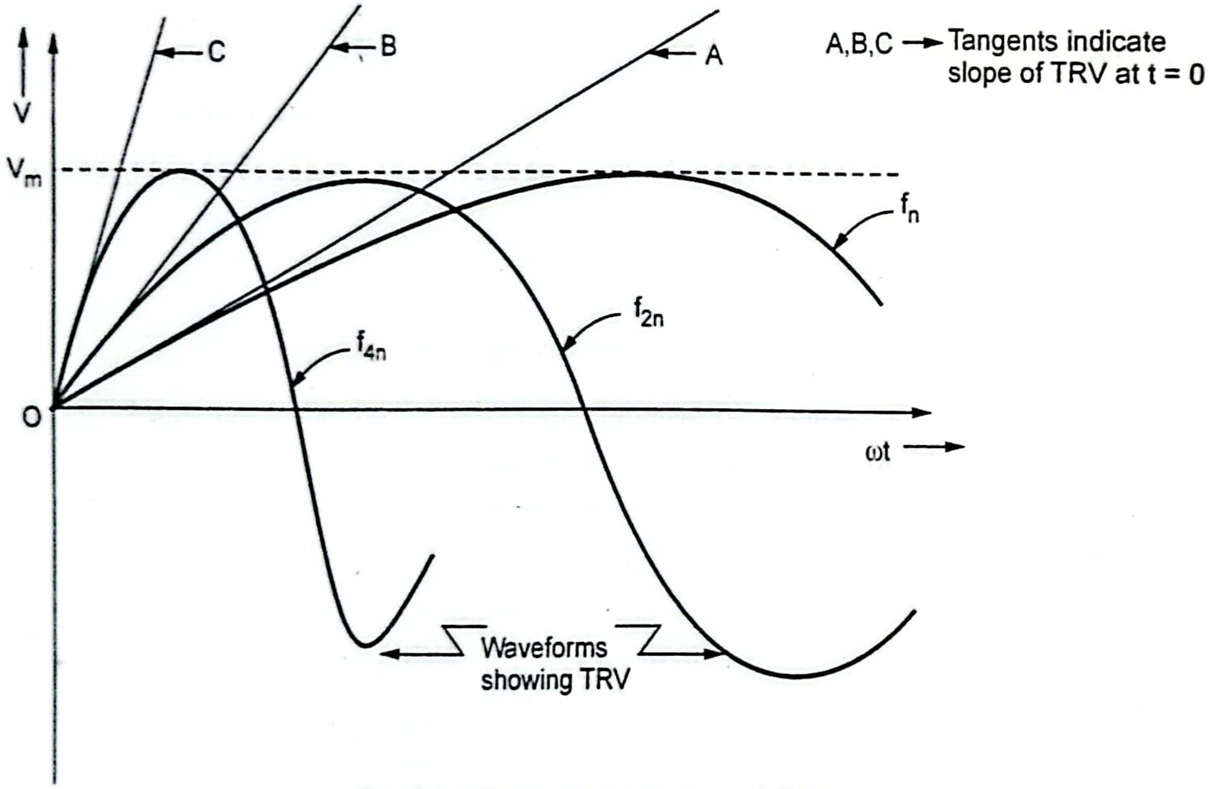


Fig. 7.8.3 Effect of frequency of TRV

Rate of rise of TRV causes voltage stress on the contact gap which will continue the arc. If the frequency is increased then relatively small time is available for building of dielectric strength of contact gap. Hence increase in frequency causes greater stresses. The rate of rise of TRV is related with the breaking capacity of a circuit breaker. Thus it also means rate of rise of TRV is dependent on natural frequency of TRV. As frequency increases the breaking capacity reduces.

7.8.2 Effect of Power Factor on TRV

At the instant of final current zero the voltage appearing across the C.B. contacts is affected by the p.f. of the current. At current zero the arc is extinguished. After this power frequency voltage appears across the circuit breaker. The instantaneous value of the voltage at current zero depends on phase angle between the current and voltage.

For unity p.f. load as shown in the Fig. 7.8.4 both voltage and current are in phase and are zero at the same instant.

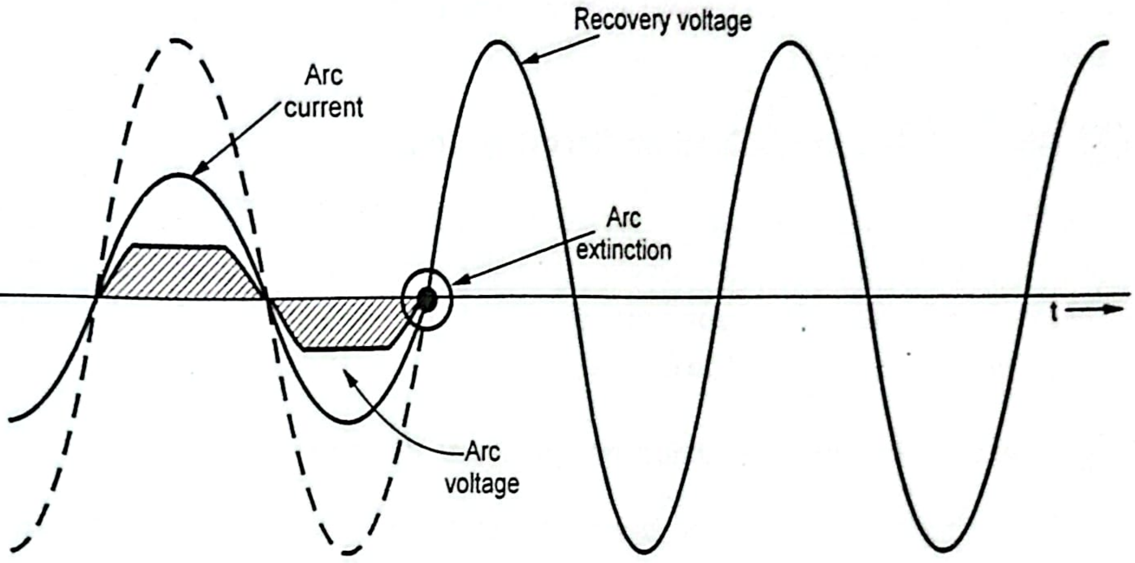

Recovery voltage
Arc
current
Arc
extinction
t
Arc
voltage

Fig. 7.8.4 Unity power factor

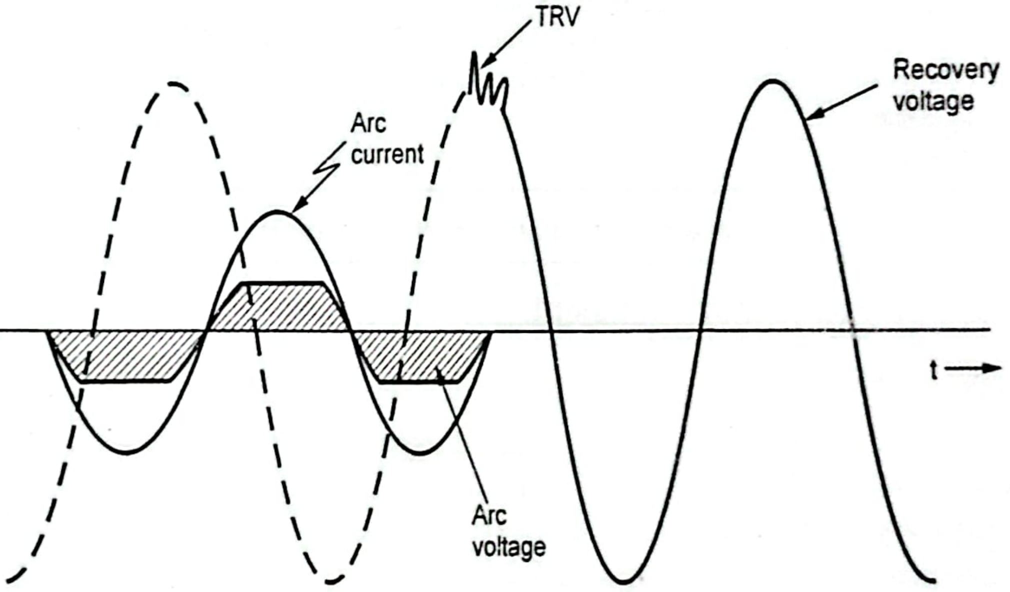

TRV
Recovery
voltage
Arc
current
t
Arc
voltage

Fig. 7.8.5 Zero power factor

If we consider zero power factor currents, the peak voltage E_{max} is impressed on the circuit breaker contacts at the current zero instant. This instantaneous voltage gives more transient and provides high rate of rise of TRV. Hence if the p.f. is low then interrupting of such current is difficult.

Review Questions

1. *What are the various factors that affect transient recovery voltage ?*
2. *Discuss the factors on which restriking voltage depends.*

7.9 Recovery Voltage

As seen previously it is the voltage having normal power frequency which appears after the transient voltage.

7.9.1 Effect of Reactance Drop on Recovery Voltage

Before fault is taking place let us consider that the voltage appearing across circuit breaker is V_1. As the fault current increases, the voltage drop in reactance also increases. After fault clearing the voltage appearing say V_2 is slightly less than V_1. The system takes some time to regain the original value.

7.9.2 Effect of Armature Reaction on Recovery Voltage

The short circuit currents are at lagging power factor. These lagging p.f. currents have a demagnetizing armature reaction in alternators. Thus the induced e.m.f. of alternators decreases. To regain the original value this e.m.f. takes some time. Thus the power frequency component of recovery voltage is less than the normal value of system voltage.

Review Question

1. *State the effect of reactance drop and armature reaction on recovery voltage.*

7.10 Single Frequency Transient

Consider the circuit shown in the Fig. 7.10.1. This circuit produces the single frequency restriking voltage transient.

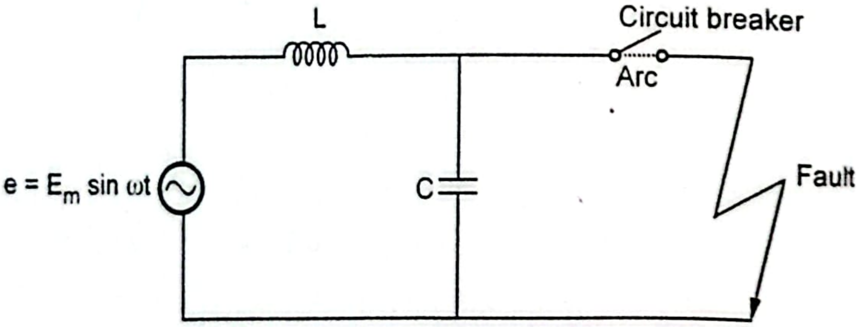


Fig. 7.10.1

The natural frequency of oscillation is given by,

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

where L = Inductance in henry, C = Capacitance in farads

Depending upon the values of L and C, the frequency ranges from 10 Hz to 10 kHz. The circuit configuration in actual power system is complicated and it has distributed capacitance and inductances. In such circuits the TRV has several components of frequencies which is shown in the Fig. 7.10.2.

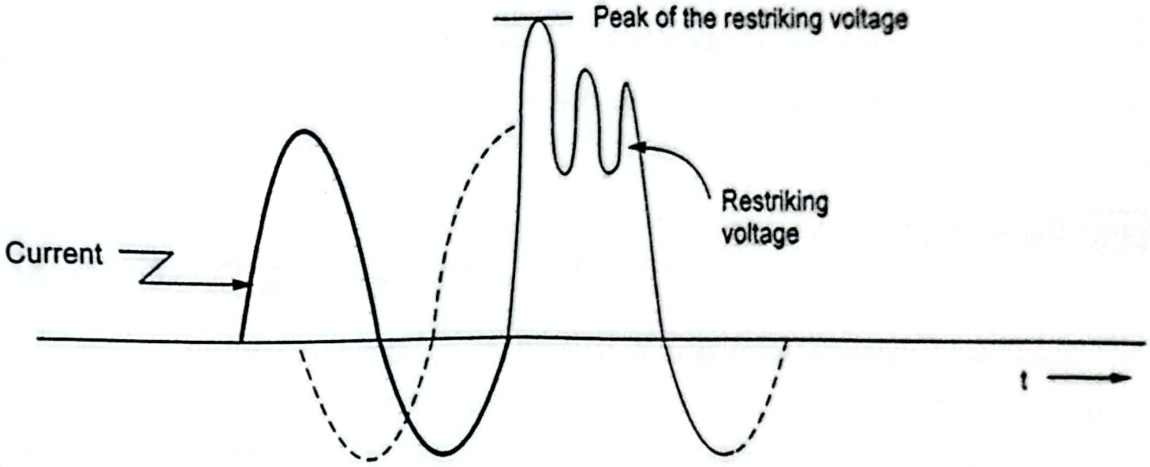

Peak of the restriking voltage
Restriking voltage
Current
t

Fig. 7.10.2

The transient shown in the Fig. 7.10.2 is obtained by operating the terminal fault where reactance between the fault and circuit breaker is negligible.

7.11 Double Frequency Transient

In last section we have considered inductance L and capacitance C on only one side of circuit breaker. But it may be on both sides of circuit breaker. This is shown in the Fig. 7.11.1.

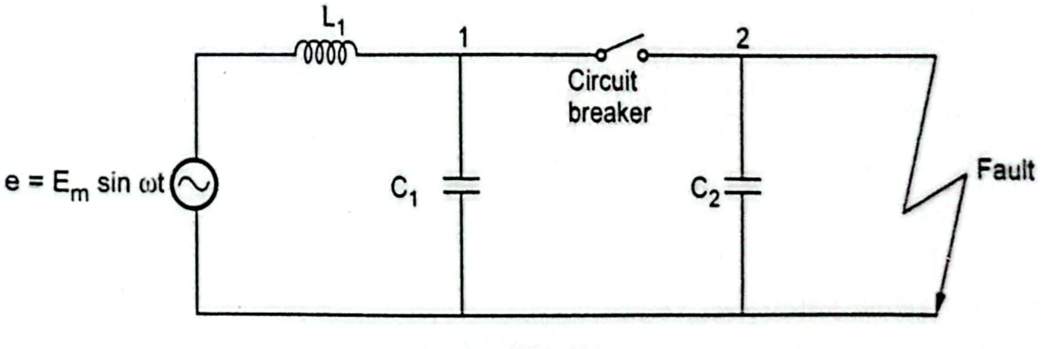

L_1
1
2
Circuit breaker
$e = E_m \sin \omega t$
C_1
C_2
Fault

Fig. 7.11.1

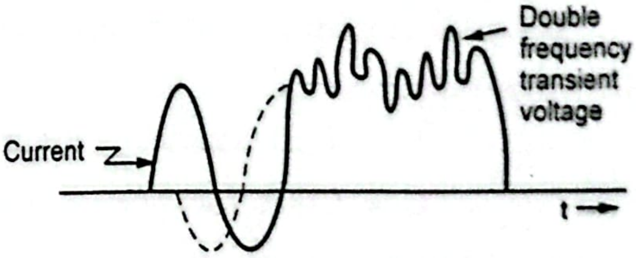

Double frequency transient voltage
Current
t

Fig. 7.11.2

The points 1 and 2 are equipotential points before clearing the fault. But after the arc extinction there will be two circuits which may oscillate at their own natural frequencies and thus a composite double frequency transient appears across circuit breaker. This is shown in the Fig. 7.11.2.

The circuit configuration, the type of fault and the type of neutral earthing are the important factors which will decide the frequency, rate of rise and peak value of the TRV.

The TRV wave is defined by specifying the peak value and time required to reach the same or it can be specified by defining the segment of lines which enclose the TRV waveform.

7.12 Derivation of Rate of Rise of TRV

AU : May-04,05,07,08,12,15, Dec.-04,06,08,11,13,14,16

As seen previously the transient voltage that appears across the circuit breaker contacts at the instant of arc extinction is called restriking voltage. The rate of rise of restriking voltage RRRV is nothing but rate which is expressed in volts per microsecond. This will represent the rate at which transient recovery voltage is increasing. The rate of rise of TRV is dependent on system parameters.

With e as the restriking voltage in volts then

$$\text{RRRV} = \frac{de}{dt} \text{ volts}/\mu\text{sec}$$

The maximum instantaneous value attained by the restriking voltage is called the peak restriking voltage.

With the given specifications of TRV the circuit breaker must be able to interrupt the short circuit breaking current. The peak value of TRV, time to reach the peak frequency of TRV and initial rate of rise are some of the important properties of TRV which are significant.

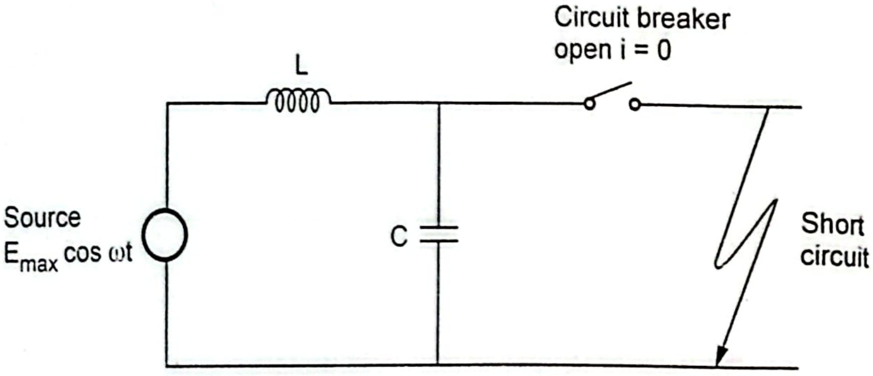


Fig. 7.12.1

Consider a simplest form of an equivalent circuit shown in the Fig. 7.12.1.

In this simplified case,

L = Total inductance between circuit breaker and source

C = Capacitance to earth of the circuit.

Circuit resistance is neglected.

A short circuit is applied directly at the terminals of circuit breaker, remote from source.

Initially circuit breaker is closed and at that time current flowing through it is 'i'

$$i = \frac{E_m}{\omega L} \cos(\omega t - 90°) \quad \text{i.e.} \quad i = \frac{E_m}{\omega L} \sin \omega t,$$

If the applied source voltage is $E_m \cos \omega t$, since the effect of 'C' can be neglected as it is short circuited by the breaker switch.

When circuit breaker is opened, then if current is to be interrupted this can be simulated by assuming a cancelling current equal and opposite to original current, being injected at circuit breaker. The voltage necessary to cause this current is then voltage that appears across circuit breaker contacts immediately after interruption.

Looking at circuit from the breaker terminals L and C appear in parallel and the equation of cancelling current is,

$$i = \frac{1}{L}\int e\,dt + C\frac{de}{dt} \qquad \text{... (7.12.1)}$$

where e = Voltage across breaker terminals nothing but restriking voltage

Differentiating (7.12.1), $$\frac{di}{dt} = \frac{e}{L} + C\frac{d^2e}{dt^2} \qquad \text{... (7.12.2)}$$

The solution of 'e' will thus depend on the current and if interruption takes place at current zero i.e. when t = 0 then,

$$i = \frac{E_m}{\omega L}\sin \omega t$$

And after opening of circuit breaker,

$$\frac{di}{dt} = \frac{E_m}{\omega L}\cdot \omega \cos \omega t = \frac{E_m}{L}\cos \omega t \qquad \text{at } t = 0$$

Substituting this in (7.12.2), $$\frac{E_m}{L}\cos \omega t = \frac{e}{L} + C\frac{d^2e}{dt^2}$$

This is standard equation and solution of this equation is,

$$\boxed{e = E_m\left[1-\cos\left(\frac{t}{\sqrt{LC}}\right)\right]} \qquad \text{... (A)}$$

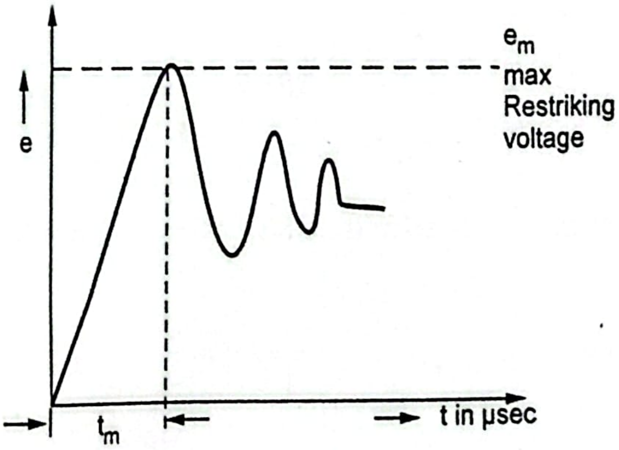


Fig. 7.12.2

This is an expression for **restriking voltage** in which,

E_m = Peak value of recovery voltage phase to neutral in volts.

t = Time in sec.

L = Inductance in henries

C = Capacitance in farads

e = Restriking voltage

7.12.1 Expression for Maximum Value of Restriking Voltage E_m and Corresponding Time t_m

$$e = E_m\left[1-\cos\left(\frac{t}{\sqrt{LC}}\right)\right]$$

if 'e' is to be maximum

$$\cos\left(\frac{t_m}{\sqrt{LC}}\right) = -1 \qquad \text{where } t = t_m$$

$$\therefore \qquad \frac{t_m}{\sqrt{LC}} = \pi$$

∴ Time at which maximum restriking voltage occurs is,

$$\boxed{t_m = \pi\sqrt{LC}}$$

And peak value of restriking voltage, $e_m = E_m\left[1-\cos\left(\frac{\pi\sqrt{LC}}{\sqrt{LC}}\right)\right]$

$$\therefore \qquad e_m = E_m[1-(-1)] \qquad \text{i.e.} \qquad \boxed{e_m = 2\,E_m}$$

where E_m is equal to active recovery voltage (i.e. instantaneous value of recovery voltage at current zero).

7.12.2 Expression for RRRV and Maximum RRRV

$$\text{Now} \qquad \text{RRRV} = \frac{de}{dt} = \frac{d}{dt}\left[E_m\left(\cos\left[\frac{t}{\sqrt{LC}}\right]\right)\right]$$

$$\therefore \qquad \boxed{\text{RRRV} = \frac{E_m}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}}$$

$$\text{and} \qquad \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} \quad \text{when} \quad \sin\frac{t}{\sqrt{LC}} = 1$$

$$\text{i.e.} \qquad \frac{t}{\sqrt{LC}} = \frac{\pi}{2}$$

$$\boxed{t = \frac{\pi\sqrt{LC}}{2}} \qquad \text{for maximum RRRV}$$

7.12.3 Frequency of Oscillation of Restriking Voltage (Transient)

$$f_n = \frac{1}{2\pi\sqrt{LC}} \quad \text{i.e.} \quad \sqrt{LC} = \frac{1}{2\pi f_n}$$

$$\therefore \quad \text{Maximum RRV} = \frac{E_m}{\sqrt{LC}} = 2\pi f_n E_m$$

$$\boxed{\text{Maximum RRV} = 2\pi E_m f_n}$$

7.12.4 Restriking Voltage under Various Conditions

The restriking voltage 'e' under various conditions will be,

$$e = V_{ar}\left(1-\cos\left[\frac{t}{\sqrt{LC}}\right]\right)$$

where V_{ar} active recovery voltage i.e. the instantaneous value of recovery voltage at current zero and V_{ar} can be written as

$$\boxed{V_{ar} = K_1 K_2 K_3 E_m}$$

Here E_m is the peak value of system voltage where,

K_1 is factor which takes into accounts effect of circuit p.f. and $K_1 = \sin\phi$

So if $\phi = 90°, \quad K_1 = 1$

K_2 is factor which accounts effect of armature reaction on recovery voltage.

K_3 is phase factor or first pole to clear factor.

7.12.5 First Pole to Clear Factor

The first pole to clear factor is given by,

$$\boxed{\text{First pole to clear factor} = \frac{\text{RMS voltage between healthy phase and faulty phase}}{\text{Phase to neutral voltage with fault removed}}}$$

In three phase systems if fault does not involve the earth, the voltage across the circuit breaker pole first to clear is 2.5 times the phase voltage. The arc extinction in the three poles of three phase circuit breakers is not simultaneous as currents are 120° out of phase. In practical systems the recovery voltage of the pole first to extinguish the arc is of the order of 2.2 to 2.5 times of the phase voltage.

If fault involves earth and the neutral is grounded through reactor, the recovery voltage is influenced by the equivalent system reactances.

Thus in 3 phase circuits $K_3 = 1$ if neutral is earthed and fault is also earthed. While $K_3 = 1.5$ if neutral is earthed and fault is insulated or neutral is insulated and fault is earthed.

Example 7.12.1 *In short circuit test on a 3 pole, 132 kV circuit breaker, the following observations are made p.f. of fault 0.4, recovery voltage 0.9 times full line value, the breaking current symmetrical, frequency of oscillations of restriking voltage 16 kHz. Assume neutral is grounded and fault is not grounded. Determine average RRRV.*

Solution :

$$e = V_{ar}\left[1-\cos\left(\frac{t}{\sqrt{LC}}\right)\right]$$

where $V_{ar} = K_1 K_2 K_3 E_m$

K_1(takes into account p.f. effect) $= \sin\phi$

K_2 (takes into account armature reaction effect) ≈ 0.9

K_3 (Phase factor or 1st pole to clear factor)

$= 1$ for both neutral and fault grounded

$= 1.5$ for any one of the two not grounded.

In the problem,

$$K_1 = \sin\phi = \sin[\cos^{-1} 0.4] = 0.9165$$

$$K_2 = 0.9 \quad K_3 = 1.5$$

Peak value of voltage i.e. line to ground

$$E_m = \frac{132}{\sqrt{3}} \times \sqrt{2} = 107.77 \text{ kV}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} \quad \therefore \quad \frac{1}{\sqrt{LC}} = 2\pi f_n = 2\pi \times 16 \times 10^3 = 1 \times 10^5$$

Time to reach maximum restriking voltage

$$\text{Maximum } t_m = \pi\sqrt{LC} = \frac{\pi}{1\times 10^5}$$

Maximum restriking voltage $= 2 V_{ar} = 2 K_1 K_2 K_3 E_m$

$$= 2 \times 0.9165 \times 0.9 \times 1.5 \times 107.77 \times 10^3 = 2.66682 \times 10^5 \text{ V}$$

Average RRRV,

$$\frac{\text{Maximum restriking voltage}}{\text{Time to reach maximum restriking voltage}} = \frac{2.66682\times10^5}{\pi/1\times10^5}$$

$$= 8.48\times10^9 \text{ V/sec} = 8.48\times10^6 \text{ kV/sec} = \mathbf{8.48 \text{ kV}/\mu\text{sec}}$$

Example 7.12.2 *In a short circuit test on a 130 kV, 3 phase system, the breaker gave the following results : p.f. of fault 0.45, recovery voltage 0.95 times full line voltage, breaker current symmetrical, and restriking transient had a natural frequency 16 kHz. Determine average RRRV. Assume fault is grounded.*

Solution :

$$E_m = \frac{\sqrt{2}\times130}{\sqrt{3}} = 106.144 \text{ kV}$$

$$\therefore \quad V_{ar} = K_1 K_2 K_3 E_m \qquad \text{where } K_1 = \sin\phi = 0.8930$$

$$= 0.8930\times0.95\times1\times106.144 \qquad K_2 = 0.95$$

$$= 90.047262 \text{ kV} \qquad K_3 = 1$$

$$\therefore \quad \text{Maximum e} = 2V_{ar} = 180.09452 \text{ kV}$$

$$\text{Maximum time} = \pi\sqrt{LC} \quad \text{and} \quad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum t} = \frac{1}{2f_n} = \frac{1}{2\times16\times10^3}$$

$$\therefore \text{Average RRRV} = \frac{\text{Maximum e}}{\text{Maximum t}} = \frac{180.09452}{1/2\times16\times10^3} = \mathbf{5.76302 \text{ kV}/\mu\text{sec}}$$

Example 7.12.3 *Calculate the RRRV of 132 kV circuit breaker with neutral earthed. S.C. data as follows: Broken current is symmetrical, restriking voltage has frequency 20 kHz, p.f. 0.15. Assume fault is also earthed.*

Solution : $K_1 = \sin\phi = \sin(\cos^{-1} 0.15) = 0.9886, K_2 = 1$

$$K_3 = 1 \qquad \text{both grounded}$$

$$E_m = \frac{\sqrt{2}\times132}{\sqrt{3}} = 107.77755 \text{ kV}$$

$$\therefore \quad V_{ar} = K_1 K_2 K_3 E_m = 106.54889 \text{ kV}$$

$$\therefore \quad \text{Maximum e} = 2V_{ar} = 213.09778 \text{ kV}$$

$$t_m = \pi\sqrt{LC}$$

and $$f_n = \frac{1}{2\pi\sqrt{LC}} \qquad \therefore \quad \pi\sqrt{LC} = t_m = \frac{1}{2f_n} \text{ sec}$$

$$\therefore \text{ Maximum } t_m = \frac{1}{2\times 20\times 10^3} \text{ sec}$$

$$\therefore \quad \text{RRRV} = \frac{e_{max}}{t_{max}} = \frac{213.09778}{[1/(20\times 10^3\times 2)]} = \mathbf{8.52 \text{ kV}/\mu\text{sec}}$$

Example 7.12.4 *A 50 Hz generator has e.m.f. to neutral 7.5 kV (r.m.s.). The reactance of generator and the connected system is 4 Ω and distributed capacitance to neutral is 0.01μF with resistance negligible . Find,* **AU : Dec.-06, Marks 8**

i) Maximum voltage across the circuit breaker contacts

ii) Frequency of oscillations

iii) RRRV average upto first peak of oscillations.

Solution : $X = 2\pi fL = 4\ \Omega,\ L = 4\ /\ 2\pi\times 50 = 0.0127$ H.

$$E_m = \sqrt{2}\times 7.5 = 10.606 \text{ kV}$$

i) Maximum voltage $= 2\times E_m = 2\times 10.606 =$ **21.212 kV**

ii) $$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0127\times 0.01\times 10^{-6}}} = \mathbf{14.1227 \text{ kHz}}$$

iii) Maximum time to reach maximum voltage is,

$$t_m = \pi\sqrt{LC} = \frac{1}{2f_n} = \frac{1}{2\times 14.1227\times 10^3} \text{ sec}$$

$$\therefore \text{ Average RRRV} = \frac{\text{Maximum voltage}}{t_m} = \frac{21.212}{[1/(2\times 14.1227\times 10^3)]} = \mathbf{0.599 \text{ kV}/\mu \text{ sec}}$$

Example 7.12.5 *In a system having 220 kV, the line to ground capacitance 0.015 μF, inductance 3.5 H. Determine voltage appearing across pole of circuit breaker if a magnetising current of 6.5 A instantaneous is interrupted. Determine also the value of resistance to be used across the contacts to eliminate the restriking voltage.*

Solution : $$e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right)$$

$$\frac{1}{2}L\,i^2 = \frac{1}{2}C\,e^2$$

Energy stored in 'L' = Energy given to capacitor

$$\therefore \quad e = i\sqrt{L/C} \qquad \text{where } i = \text{Instantaneous value}$$

$$= 6.5\sqrt{\frac{3.5}{(0.015\times10^{-6})}} = \mathbf{99.3\ kV}$$

To eliminate restriking voltage and critical damping condition,

$$R = 0.5\sqrt{L/C} = 0.5\sqrt{\frac{3.5}{(0.015\times10^{-6})}} = \mathbf{7.635\ k\Omega}$$

Example 7.12.6 *A 50 Hz, 3 ph alternator, has rated voltage 13.5 kV, connected to circuit breaker, inductive reactance 4 Ω/ph, C = 2 μF.*

Determine maximum RRRV, peak restriking voltage, frequency of oscillations.

Solution :

$$E_m = \frac{\sqrt{2}\times13.5}{\sqrt{3}} = 11.0227\ \text{kV}$$

$$X = 2\pi f L \qquad \therefore\ L = 0.0127323\ \text{H and } C = 2\ \mu\text{F}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \mathbf{0.997\ kHz}$$

Maximum restriking voltage = 2 E_m = **22.0454 kV**

$$e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right)$$

$$\therefore \quad \frac{de}{dt} = E_m\frac{1}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}$$

This is the expression of RRRV

$$\therefore\ \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} \qquad \text{and} \qquad f_n = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad \text{Maximum RRRV} = 2\pi f_n E_m = \pi \times 0.997\times10^3\times22.0454\ \text{kV/sec} = \mathbf{0.06907\ kV/\mu sec}$$

Example 7.12.7 *A 50 cycles, 3 phase alternator with grounded neutral has inductance of 1.6 mH per phase and is connected to busbar through a circuit breaker. The capacitance to earth between the alternator and circuit breaker is 0.003 μF per phase. The circuit breaker opens when rms value of current is 7500 A. Determine the following:*

i) Maximum rate of rise of restriking voltage.

ii) Time for maximum rate of rise of restriking voltage.

iii) Frequency of oscillations

Neglect first pole to clear factor.

Solution : $i = 7500$ A, $L = 1.6$ mH, $C = 0.003\ \mu F$

$$X_L = 2\pi f L = 2\pi \times 50 \times 1.6 \times 10^{-3} = 0.50265\ \Omega$$

Peak value of active recovery voltage (Phase to neutral) i.e.

$$E_m = (i \times X_L) \times \sqrt{2} = (7500 \times 0.50265) \times \sqrt{2} = 5331.4083\ V$$

$$f_n = \text{Frequency of oscillations} = \frac{1}{2\pi\sqrt{LC}}$$

$$= \frac{1}{2\pi\sqrt{1.6\times10^{-3}\times0.003\times10^{-6}}} = \mathbf{72643.96\ Hz}$$

$$\text{Maximum RRRV} = 2\pi f_n E_m = 2\pi \times 72643.96 \times 5331.4083$$

$$= 2433443822\ V/sec = \mathbf{2433.4438\ V/\mu sec}$$

$$\text{Time for maximum RRRV} = \frac{\pi\sqrt{LC}}{2} = \mathbf{3.4414\ \mu sec}$$

Example 7.12.8 *In short circuit test on a 3 pole, 132 kV, circuit breaker, the following observations are made. Power factor for fault = 0.4, recovery voltage 0.9 times full line value, the breaking current symmetrical, frequency of oscillation of restriking voltage 16 kHZ. Assume neutral is grounded and fault is not grounded. Determine average RRRV.*

AU : May-04, Dec.-16, Marks 8

Solution : $V_L = 132$ kV, $\cos\phi = 0.4$, $f_n = 16$ kHz, Fault not grounded

$$E_m = \frac{\sqrt{2}\times132}{\sqrt{3}} = 107.77\ kV$$

$$V_{ar} = K_1 K_2 K_3 E_m \quad \text{where } K_1 = \sin\phi$$

$$\therefore \quad \phi = \cos^{-1} 0.4 = 66.42°, K_1 = \sin 66.42° = 0.9165$$

$$K_2 = 0.9 \text{ (given)},\ K_3 = 1.5 \text{ as fault not grounded}$$

$$\therefore \quad V_{ar} = 0.9165\times0.9\times1.5\times107.77 = 133.341\ kV$$

$$\text{Maximum restriking voltage } e = 2\,V_{ar} = 266.68\ kV$$

$$\text{Maximum time } t = \frac{1}{2 f_n} = \frac{1}{2\times16\times10^3} = 3.125\times10^{-5}\ sec.$$

$$\therefore \quad \text{Average RRRV} = \frac{\text{Maximum restriking voltage}}{\text{Maximum time t}} = \frac{266.68\times10^3}{3.125\times10^{-5}}$$

$$= 8.53\times10^9\ V/s = \mathbf{8.53\ kV/\mu sec.}$$

Example 7.12.9 *A 3-phase alternator has the line voltage of 11 kV. The generator is connected to a circuit breaker. The inductive reactance upto the circuit breaker is 5Ω/phase. The distributed capacitance upto circuit breaker between phase and neutral is 0.001 μF. Determine peak restriking voltage across the CB, frequency of restriking voltage transients, average rate of restriking voltage upto peak restriking voltage, maximum RRRV.*

AU : Dec.-04, Marks 6

Solution :

$$E_m = \frac{\sqrt{2}\times 11}{\sqrt{3}} = 8.98 \text{ kV}, \ C = 0.001\ \mu F$$

$$X = 2\pi f L \quad \text{i.e.} \quad L = \frac{X}{2\pi f} = \frac{5}{2\pi(50)} = 0.01591 \text{ H}$$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(0.01591)(0.001\times10^{-6})}} = \mathbf{39901.11\ Hz.}$$

Maximum restriking voltage = $2E_m = 2(8.98) = 17.96$ kV

$$e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right)$$

$$\therefore \quad \frac{de}{dt} = E_m \frac{1}{\sqrt{LC}} \sin\frac{t}{LC}$$

This is the expression of RRRV

$$\therefore \text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} = \frac{8.98}{\sqrt{(0.01591)(0.001\times10^{-6})}} = \mathbf{2.251\ kV/\mu sec}$$

$$\text{Average RRRV} = \frac{\text{Maximum } e}{\text{Maximum } t} = \frac{2\times 8.98}{(1/2 f_n)} = \frac{17.96}{(1/2\times 39901.11)} = \mathbf{1.43\ kV/\mu sec}$$

Example 7.12.10 *In a short circuit test on a circuit breaker the following readings were observed on a single frequency transient time to reach the peak recovery voltage 40 μsec and the peak restriking voltage 100 kV. Determine the average RRRV and the frequency of oscillations.*

AU : May-05, Marks 8

Solution : Average RRRV is given as,

$$\text{Average RRRV} = \frac{\text{Peak restriking voltage } (E_m)}{\text{Time to reach the peak } (t_m)} = \frac{100\times10^3}{40} = 2500$$

∴Average RRRV=2500 V/μsec

Natural frequency f_n is given by,

$$f_n = \frac{1}{2\cdot t_m} = \frac{1}{2(40\times10^{-6})} = \frac{1}{80\times10^{-6}} = 12500 \text{ Hz}$$

$$\therefore \quad f_n = \mathbf{12.5\ kHz.}$$

Example 7.12.11 *A 50 Hz, 11 kV, 3 phase alternator with earthed neutral has a resistance of 5 ohms per phase and is connected to a bus bar through a ciucit breaker. The distributed capacitance upto circuit breaker between phase and neutral is 0.01 μF. Determine 1) Peak restriking voltage across the contacts of the breaker 2) Frequency of oscillation 3) Average rate of rise of restriking voltage upto the first peak.* **AU : May-07, Marks 8**

Solution :

$$E_m = \frac{\sqrt{2}\times 11}{\sqrt{3}} = 8.98 \text{ kV}$$

$$X = 2\pi fL; \quad L = \frac{X}{2\pi f} = \frac{5}{2\pi\times 50} = 0.0159 \text{ H}$$

Capacitance, $C = 0.01\ \mu\text{F}$

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.0159\times 0.01\times 10^{-6}}} = \mathbf{12.621\ kHz}$$

Peak restriking voltage $= 2\,E_m = 2\times 8.98 = \mathbf{17.96\ kV}$

$$\text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} = \frac{8.98}{\sqrt{(0.0159)(0.01\times 10^{-6})}} = 712.160 \text{ kV}$$

$$\text{Average RRRV} = \frac{\text{Maximum e}}{\text{Maximum t}} = \frac{2\times 8.98}{(1/2f_n)}$$

$$= \frac{17.96}{\left[\dfrac{1}{2\times 12.621\times 10^3}\right]} = \mathbf{453.34\times 10^3\ V/sec = 453.34\ \ kV/sec}$$

Example 7.12.12 *For a 132 kV system, the reactance and capacitance upto the location of the circuit breaker is 3 ohms and 0.015 μF respectively.*

Calculate :

1) The frequency of transient oscillation.

2) Maximum value of restriking voltage.

3) Maximum value of RRRV.

Solution : $E_{rms} = 132$ kV, $X_L = 3\ \Omega$, $C = 0.015\ \mu$F

$$E_m = \frac{\sqrt{2}\times 132}{\sqrt{3}} = 107.77 \text{ kV}$$

$$X_L = 2\pi fL \quad \text{i.e.} \quad L = \frac{X_L}{2\pi f} = \frac{3}{2\pi\times 50} = 9.55 \text{ mH}$$

$$\therefore \quad f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(9.55\times 10^{-3})(0.015\times 10^{-6})}} = \mathbf{13.29\ kHz}$$

Maximum restriking voltage $= 2E_m = 2\,(107.77) = \mathbf{215.54\ kV}$

Maximum RRRV can be calculated as,

$$e = E_m\left(1-\cos\frac{t}{\sqrt{LC}}\right)$$

$$\therefore \quad \frac{de}{dt} = E_m \cdot \frac{1}{\sqrt{LC}}\sin\frac{t}{\sqrt{LC}}$$

$$\text{Maximum RRRV} = \frac{E_m}{\sqrt{LC}} \text{ and } f_n = \frac{1}{2\pi\sqrt{LC}} \quad \therefore \sqrt{LC} = \frac{1}{2\pi f_n}$$

$$\therefore \quad 2\pi f_n = \frac{1}{\sqrt{LC}}$$

$$\text{Maximum RRRV} = 2\pi f_n E_m = \pi \times f_n \times (2E_m)$$

$$= \pi \times 13.29 \times 10^3 \times (215.54) = 8.99 \text{ kV}/\mu\text{sec}$$

Review Questions

1. *Derive the expressions for restriking and rate of rise of recovery voltages.*

   AU : May-04,12, Marks 16, Dec.-04, Marks 10, May-05, Marks 12, Dec.-08,11,13,16, May-08, 15, Marks 8

2. *A 3 phase alternator has line voltage of 11 kV. The generator is connected to a circuit breaker. The inductive reactance upto circuit breaker is 5 Ω per phase. The distributed capacitance upto circuit breaker between phase and neutral is 0.01 μF. Determine*
   a) Peak restriking voltage across circuit breaker
   b) Frequency of restriking voltage transient
   c) Average rate of restriking voltage upto peak restriking voltage
   d) Maximum RRRV **(Ans. : 18 kV; 12637 c/s ; 0.456 kV/μsec; 714 V/μsec)**

3. *In a short circuit test on a 3 pole circuit breaker of fault was 0.4, the recovery voltage was 0.95 times full line voltage. The breaking current was symmetrical. The frequency of oscillations of restriking voltage was 15000 c/s. Estimate the average rate of rise of restriking voltage. The neutral is grounded and fault involves earth. Neglect first pole to clear factor.*

   (Ans. : 4.8 kV/μsec)

4. *Explain the terms : Restriking voltage, recovery voltage and RRRV. Derive expressions for restriking voltage and RRRV.* **AU : Dec.-14, Marks 16**

7.13 Interruption of Capacitive Currents

AU : May-04,05,08,11,12,14,15,17,19, Dec.-13,15,16

In power systems capacitor banks are used in the network which supplies reactive power at leading power factor. There are various conditions such as opening a long transmission line on no load or disconnecting a capacitor bank etc., in which it is required to interrupt the capacitive currents which is a difficult task for the circuit breakers. To understand this difficulty let us consider a simple circuit shown in the Fig. 7.13.1.

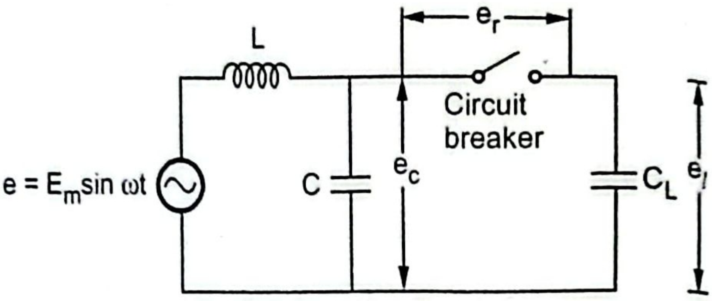

e_r
L
Circuit breaker
$e = E_m \sin \omega t$
C
e_c
C_L
e_l

Fig. 7.13.1 Interruption of capacitive currents

The value of load capacitance C_L is greater than C. The voltage across a capacitor cannot change instantaneously. The currents supplied to the capacitor are generally small and interruption of such currents take place at first current zero. Also at the beginning, the rate of rise of recovery voltage is low and increases slowly. Whenever such circuit is opened a charge is trapped in the capacitance C_L. The voltage e_L across the load

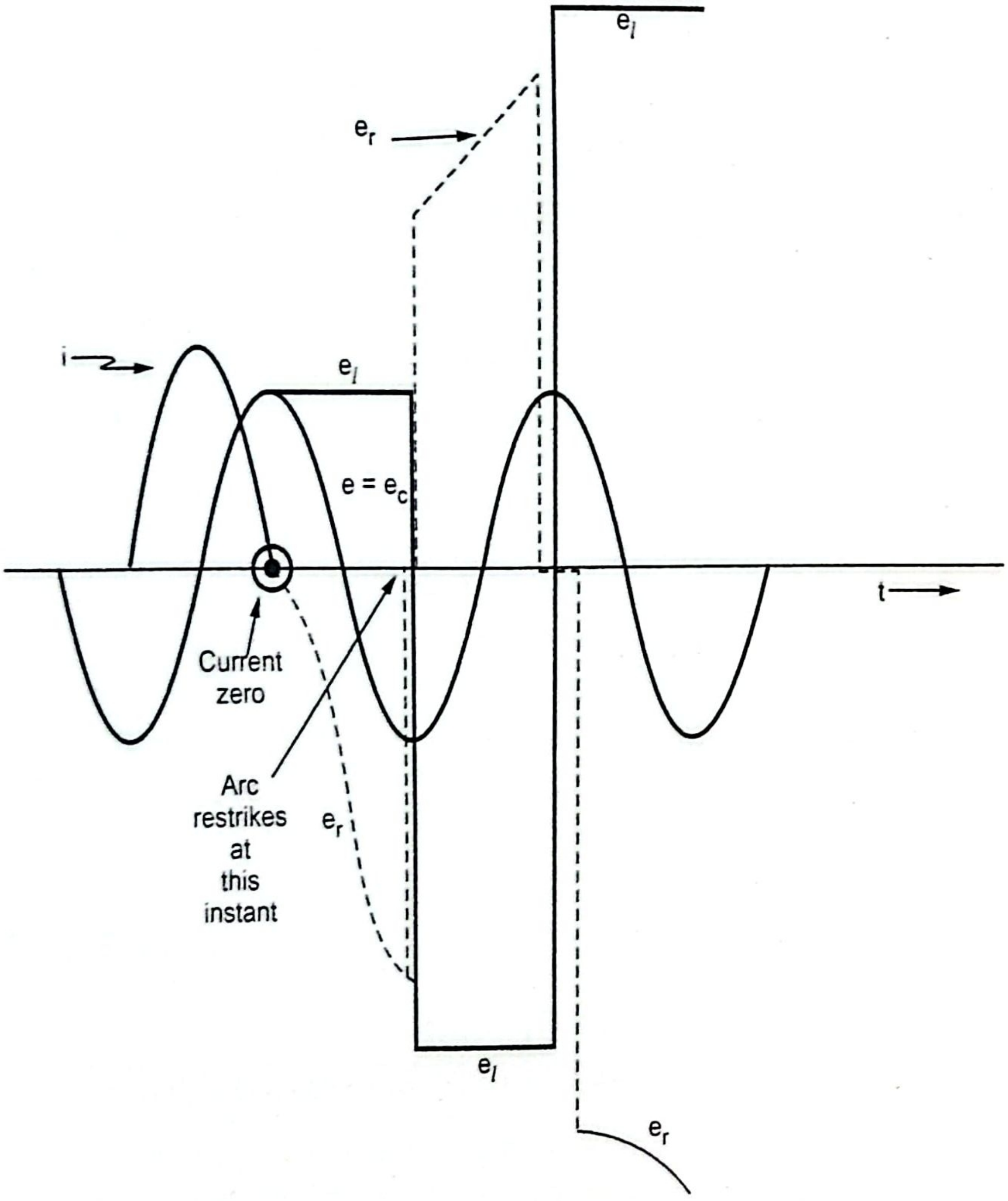

i
e_l
e_r
$e = e_c$
Current zero
Arc restrikes at this instant
e_r
t
e_l
e_r

Fig. 7.13.2 Waveform showing interruption of capacitive current

capacitance will hold the same value when circuit was opened. This voltage is nothing but peak of supply voltage as power factor angle is nearly 90° leading.

After opening the circuit the voltage V_C across the capacitance C oscillates and approaches a new steady value. But due to small value of capacitance C, the value attained is close to the supply voltage. The recovery voltage e_r is nothing but difference between e_C and e_L. Its initial value is zero as the circuit breaker will be closed and increases slowly in the beginning. When V_C reverses after half cycle, the recovery voltage is about twice the normal peak value. Therefore it is possible that at this instant arc may restrike as the electrical strength between the circuit breaker contacts is not sufficient. The circuit will be reclosed and e_L oscillates at a high frequency.

The supply voltage at this instant will be at its negative peak; therefore a high frequency oscillation takes place.

At the instant of restrucking the arc, the recovery voltage V_r is zero. The voltage across the load capacitance reaches – 3 times the peak value of normal supply voltage. The recovery voltage then starts increasing. If again restriking of arc takes place, a high frequency of oscillation of e_L takes place. Such several repetitions of the restriking cycle will increase the voltage across load capacitance to a dangerously high value. In practice this voltage is limited to 4 times the normal peak of the voltage. This is represented in the Fig. 7.13.2. (See Fig. 7.13.2 on previous page)

Thus in the successive restrikes, the energy $\frac{1}{2}CV^2$ is to be dissipated which is quite large and the circuit breaker may get damaged in the process of restriking. Hence the circuit breakers those are to be used for capacitors must be free from restriking and should have adequate rating for capacitive current switching so that severe voltage transients can be avoided.

If circuit breakers are closed while switching capacitor banks in parallel, the pre-arcing that is arc is struck before contacts touch together, takes place. This may damage the contacts as the energy in the arc is converted into heat. Thus while switching, with capacitor banks suitable reactor L must used in series to limit high frequency inrush current.

Review Question

1. *Write a brief note on interruption of capacitive current.*

AU : May-11, Marks 5, May-04, 05, 08, 12, 14, 15, 17,19, Dec.-13, 15, 16, Marks 8

7.14 Current Chopping (Interruption of Low Magnetizing Current)

AU : Dec.-04,08,11,12,13,15,17, May-11,12,13,14,15,17,18,19,22

There are certain circumstances like disconnecting transformers on no load in which it is necessary to interrupt small inductive currents. The no-load current of a transformer is almost at zero power factor lagging. This current is normally smaller than the normal current rating of the breaker. Interrupting such current causes severe duty on the circuit breaker. This phenomenon is called current chopping.

Consider the circuit shown in the Fig. 7.14.1 (a).

While interrupting low inductive currents the rapid deionization of contact space and blast effect may cause the current to reduce abruptly to zero, well before the natural current zero. This current chopping causes very serious voltage oscillations.

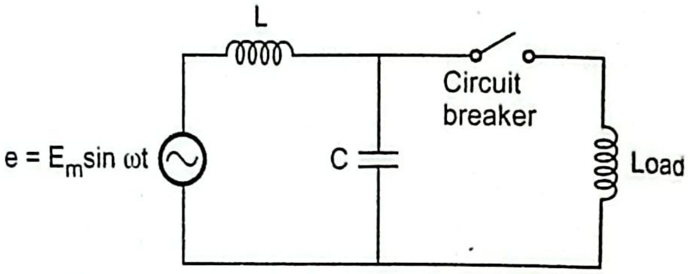


Fig. 7.14.1 (a) Circuit diagram showing interruption of inductive currents

Let the arc current be i when it is chopped down to zero value. The stored energy in the inductor which $\frac{1}{2}$ L i^2 will be discharged in to the capacitance so that the capacitor is charged to a prospective voltage V such that,

$$\frac{1}{2} L i^2 = \frac{1}{2} CV^2$$

$$\therefore \quad V = i\sqrt{L/C} \text{ volts}$$

This prospective voltage is extremely high as compared to the normal system voltage. The frequency of natural oscillations is given by,

$$f_n = \frac{1}{2\pi\sqrt{LC}}$$

To understand this point let us consider a small example of 220 kV circuit breaker interrupting a magnetizing current of 10 A r.m.s. of transformer. Let the current be chopped at the instantaneous value of 7 A. Let the value of inductance and capacitance be 35 H and 0.0020 μF.

Assuming that all the inductive energy is transferred to capacitance and using the above formula,

$$e = 7\left[\sqrt{\frac{35}{0.0020\times10^{-6}}}\right]$$

$$\therefore \quad e = 926 \text{ kV}$$

This voltage will appear across the circuit breaker contacts. Such a transient voltage having high RRRV appears across the contacts. There will be restriking of arc at some point. If the arc restrikes further, chop may occur. Thus before final interruption of current there will be many chops and the circuit breaker will fail to clear the fault. Alternately if the restrike does not occur, the severe voltage stress will appear across circuit breaker contacts.

The rise of voltage before restriking is an important factor. The lower is the rate of rise, more is the time required for deionization and high voltage will be reached.

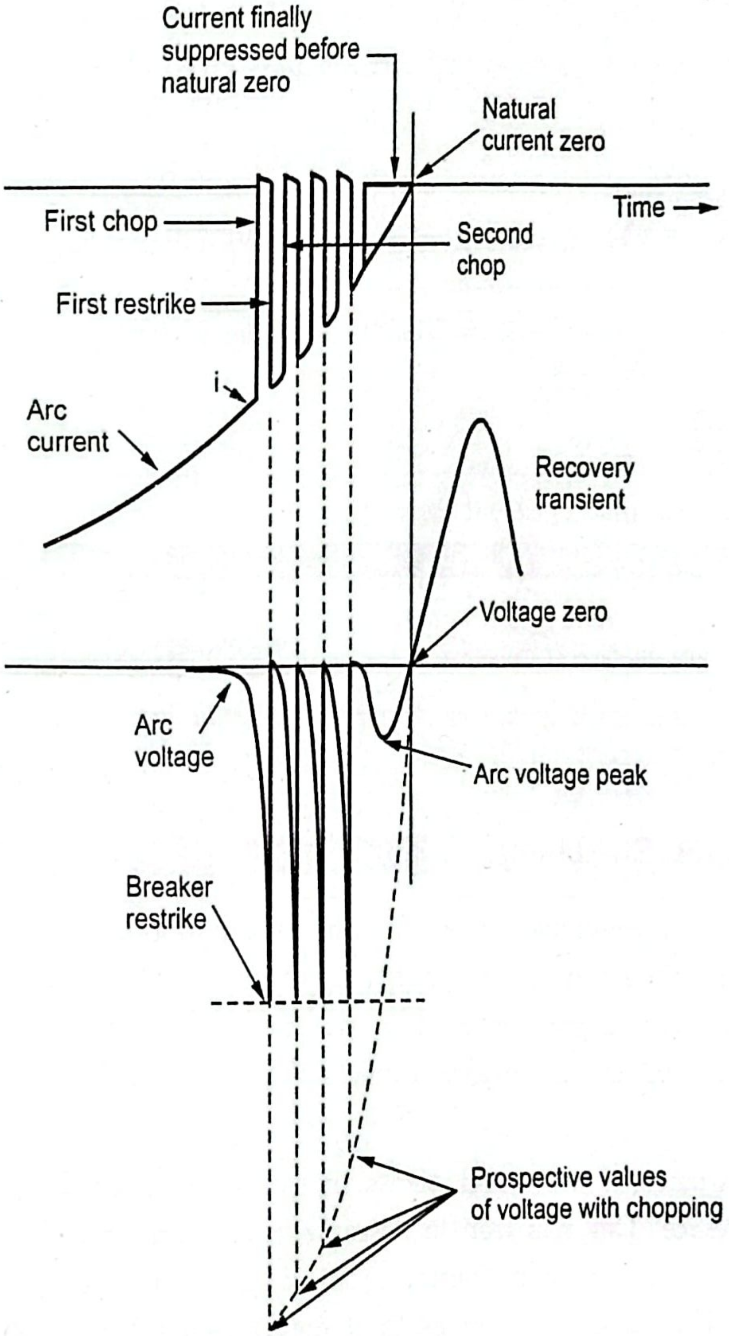

Current finally suppressed before natural zero
Natural current zero
Time
First chop
Second chop
First restrike
i
Arc current
Recovery transient
Voltage zero
Arc voltage
Arc voltage peak
Breaker restrike
Prospective values of voltage with chopping

Fig. 7.14.1 (b)

After first chopping the deionizing force which is still in action acts and second chop of current takes place. But the arc current is now smaller than the previous one and arc current collapses and restriking voltage is again build. Thus a sequence of chops will occur and arc will continuously decrease until a final chop brings arc current to zero. There will not be any further restriking as the gap is almost deionize. This is represented in the Fig. 7.14.1 (b).

Example 7.14.1 *What is the prospective voltage e across the stray capacitance of 0.0023 μF, when the instantaneous current chopped by circuit breaker is 7 A. The value of the inductance in the circuit is 35.2 H ?* **AU : Dec.-04**

Solution : Prospective voltage appearing across C.B. is given by,

$$e = i\sqrt{\frac{L}{C}}$$

$$L = 35.2\text{ H},\ C = 0.0023\ \mu\text{F} = 0.0023 \times 10^{-6}\text{ F},\ i = 7\text{ A}$$

$$\therefore \quad e = 7\sqrt{\frac{35.2}{0.0023 \times 10^{-6}}} = 7(123710.74) = \mathbf{865.97\ kV}$$

Review Questions

1. *Discuss the phenomenon of current chopping.*

   AU : Dec.-08, Marks 10, May-11, Marks 5, Dec.-11, Marks 4, May-12, 13, 18,19, Dec.-12, 13, 15, Marks 8

2. *Write short note on current chopping.* **AU : May-14, 15, 17, Dec.-17, Marks 8**

3. *Explain the phenomenon of current chopping in a circuit breaker and list the methods to reduce the same.* **AU : May-22, Marks 13**

7.15 Resistance Switching

AU : Dec.-04,06,07,11,12,15,17,18, May-05,13,18

It can be seen from previous sections that the interruption of low inductive currents, interruption of capacitive currents give rise to severe voltage oscillations. These excessive voltage surges during circuit interruption can be prevented by the use of shunt resistance R across the circuit breaker contacts. This process is known as Resistance Switching.

When the resistance is connected across the arc, a part of the arc current flows through the resistance. This will lead to decrease in arc current and increase in rate of deionization of the arc path and resistance of arc. This will increase current through shunt resistance. This process continues until the current through the arc is diverted through the resistance either completely or in major part. If the small value of the current remains in the arc then the path becomes so unstable that it is easily extinguished.

The resistance may be automatically switched in and arc current can be transferred. The time required for this action is very small. As shown in the Fig. 7.15.1 the arc first appears across points A and B which is then transferred across A and C.

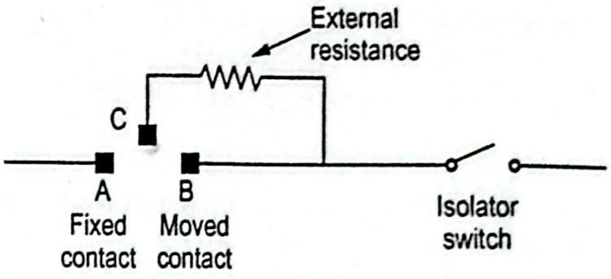

External resistance
C
A
Fixed contact
B
Moved contact
Isolator switch

Fig. 7.15.1 Typical resistor connection

The shunt resistance also ensures the effective damping of the high frequency re-striking voltage transients. This is shown in the Fig. 7.15.2.

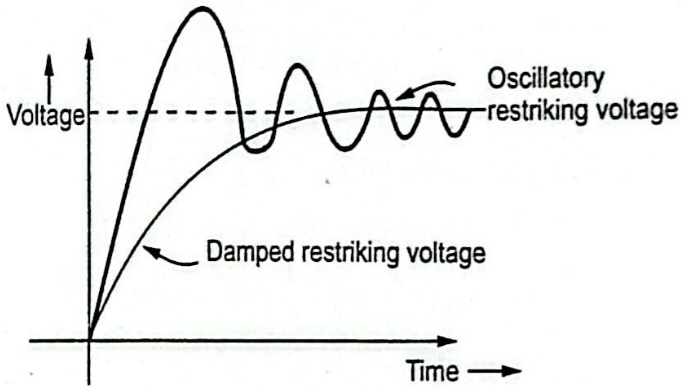
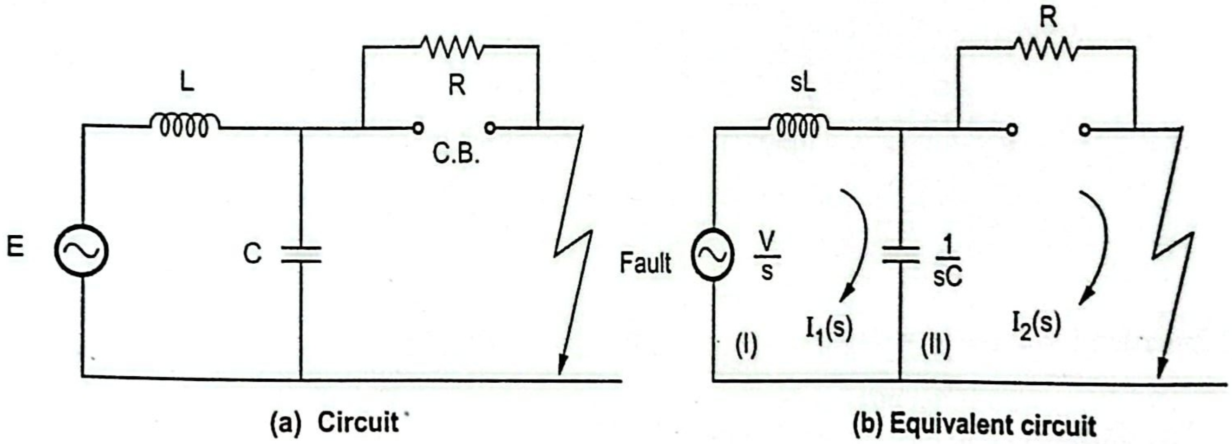


Fig. 7.15.2

We will now derive a relation which will show how damping is achieved. Consider the circuit and Laplace transform equivalent as shown in the Fig. 7.15.3.


L
R
C.B.
E
C
sL
R
Fault
$\frac{V}{s}$
$\frac{1}{sC}$
$I_1(s)$
$I_2(s)$
(I)
(II)

(a) Circuit

(b) Equivalent circuit

Fig. 7.15.3

Applying KVL to loop (I),

$$\frac{V}{s} = \left(sL+\frac{1}{sC}\right) I_1(s) - \frac{1}{sC} I_2(s) \quad \text{... (7.15.1)}$$

Applying KVL to loop (II),

$$0 = -\frac{1}{sC} I_1(s) + \left(R+\frac{1}{sC}\right) I_2(s) \quad \text{... (7.15.2)}$$

From equation (7.15.2),

$$I_1(s) = (1 + sCR)\, I_2(s)$$

Substituting this value in equation (7.15.1)

$$\frac{V}{s} = \left(sL+\frac{1}{sC}\right)\ (1 + sCR)\ I_2(s) - \frac{1}{sC}\ I_2(s)$$

$$\therefore \quad \frac{V}{s} = \left[sL+s^2RLC+\frac{1}{sC}+R-\frac{1}{sC}\right] I_2(s)$$

$$\therefore \quad \frac{V}{s} = (RLCs^2 + Ls + R)\ I_2(s)$$

$$\therefore \quad I_2(s) = \frac{V}{s\,(RLCs^2+Ls+R)} = \frac{V/RLC}{s\left(s^2+\frac{1}{RC}+\frac{1}{LC}\right)}$$

Using partial fractions,

$$I_2(s) = \frac{V}{R}\left\{\frac{1}{s}-\frac{s+\frac{1}{2RC}}{\left(s+\frac{1}{2RC}\right)^2+\frac{1}{LC}-\left(\frac{1}{2RC}\right)^2}-\frac{\frac{1}{2RC}}{\left(s+\frac{1}{2RC}\right)^2+\frac{1}{LC}-\left(\frac{1}{2RC}\right)^2}\right\}$$

Put $x = \frac{1}{2RC}, \quad y = \frac{1}{LC}-\left(\frac{1}{2RC}\right)^2$

$$I_2(s) = \frac{V}{R}\left\{\frac{1}{s}-\frac{s+x}{(s+x)^2+\left(\sqrt{y}\right)^2}-\frac{x}{(s+x)^2+\left(\sqrt{y}\right)^2}\right\}$$

Taking inverse Laplace transform,

$$i_2(t) = \frac{V}{R}\left[1-e^{-xt}\left(\cos\sqrt{y}\,t+\frac{x}{y}\sin\sqrt{y}\,t\right)\right]$$

$\therefore$ Restriking voltage, $e = R\,i_2(t) = V[1-e^{-xt}\left(\cos\sqrt{y}t+\frac{x}{y}\sin\sqrt{y}t\right)$

The damped frequency of oscillation is given by,

$$\boxed{f_d = \frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{1}{4C^2R^2}}}$$

It can be seen that with the value of the resistance R equal to or less than $\frac{1}{2}\sqrt{L/C}$, the oscillatory nature of the transient will not be there and RRRV will be within the permissible limits of circuit breaker.

For critical damping, $\boxed{R = \frac{1}{2}\sqrt{\frac{L}{C}}}$

The voltage appearing across roles of circuit breaker is given by, $V = i\sqrt{\frac{L}{C}}$

Considering different values of R, the oscillations observed are shown in the Fig. 7.15.4.

In air blast circuit breakers it is observed that the rate at which dielectric strength of gap increases is lower than in oil breakers. Since air has a much lower dielectric strength than the gases at same temperature and pressure in oil circuit breaker. The dielectric strength of a gas increases with pressure. Thus the air blast circuit breaker is more sensitive to restriking voltage transient. In low or medium voltage air blast circuit breaker the rate or rise of restriking voltage is higher. Thus shunt resistors are used for low and medium voltage air blast circuit breakers. Also in case of oil circuit breakers the resistance switching is not employed as it is not sensitive to RRRV.

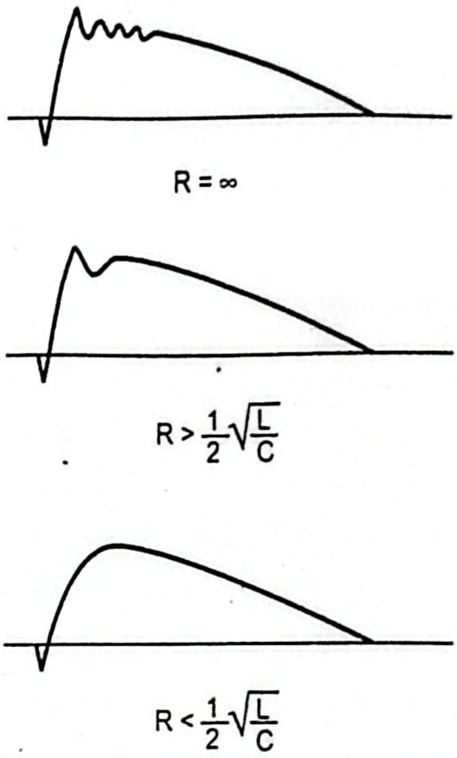


Fig. 7.15.4

Example 7.15.1 *In 132 kV transmission system, the phase to ground capacitance is 0.01 μF. The inductance being 6 H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetizing current of 10 A is interrupted. Find the value of resistance to be used across contact space to eliminate the striking voltage transient.*

Solution : $L = 6\text{ H},\ C = 0.01\ \mu\text{F} = 0.01 \times 10^{-6}\text{ F},\ i = 10\text{ A}$

Voltage appearing across poles of circuit breaker, is given by,

$$V = i\sqrt{\frac{L}{C}} = 10\sqrt{\frac{6}{0.01\times10^{-6}}} = 10\ (24494.89) = \mathbf{245\ kV}$$

The value of resistance to be used across contact space is given by,

$$R = \frac{1}{2}\sqrt{\frac{L}{C}} = \frac{1}{2}\sqrt{\frac{6}{0.01\times10^{-6}}} = \frac{1}{2}\ (24494.89) = \mathbf{12.24\ k\Omega}$$

Example 7.15.2 *In a system of 132 kV, the circuit phase to ground capacitance is 0.02 microfarad, the inductance is 5 H. Calculate the voltage appearing across the pole of a circuit breaker if a magnetic circuit of 8 A is interrupted instantaneously. Calculate the value of the pre-insertion resistor to be used across the contact space.*

AU : May-05, Marks 8

Solution : $L = 5$ H, $C = 0.02\ \mu F = 0.02 \times 10^{-6}$ F, $i = 8$ A

Voltage appearing across poles of circuit breaker is given by,

$$V = i\sqrt{\frac{L}{C}} = 8\sqrt{\frac{5}{0.02\times10^{-6}}} = 8\sqrt{250\times10^{6}} = \mathbf{126.491\ kV}$$

The value of resistance to be used across contact space is given by,

$$R = \frac{1}{2}\sqrt{\frac{L}{C}} = \frac{1}{2}\sqrt{\frac{5}{0.02\times10^{-6}}} = \frac{1}{2}(\sqrt{250\times10^{6}}) = \mathbf{7.9056\ k\Omega}$$

Example 7.15.3 *In a 132 kV, 50 Hz system, the inductance and capacitance up to the location of the circuit breaker is 25.46 mH and 0.02 μF respectively. A resistance of 600 Ω is connected across the contacts of the circuit breaker.*

Determine

i) Natural frequency of oscillations

ii) Damped frequency of oscillations and

iii) Critical value of resistance which will give no transient oscillations.

iv) The value of resistance which will give damped frequency of oscillation, one fourth of the natural frequency of oscillation. **AU : Dec.-18, Marks 15**

Solution : $L = 0.02546$ H, $C = 0.02\ \mu F$, $R = 600\ \Omega$

i) Frequency of natural oscillations is given by,

$$f_n = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{(0.02546)\,(0.02\times10^{-6})}}$$

$$= \frac{1}{2\pi\sqrt{5.092\times10^{-10}}} = 7.053\ \text{kHz}$$

ii) Damped frequency of oscillations is given by,

$$f_d = \frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{1}{4C^2R^2}}$$

$$= \frac{1}{2\pi}\sqrt{\frac{1}{(0.02546)\,(0.02\times10^{-6})} - \frac{1}{4\times(0.02\times10^{-6})^2\,(600)^2}}$$

$$= \mathbf{2.4015\ kHz}$$

iii) The critical value of resistance which will give no transient oscillation is given by,

$$R_C = \frac{1}{2}\sqrt{\frac{L}{C}} = \frac{1}{2}\sqrt{\frac{0.02546}{0.02\times10^{-6}}} = \mathbf{564.136\ \Omega}$$

iv) Let $R_1 = 600\ \Omega$ and R_2 be the resistance which will give damped frequency of oscillations one fourth of the natural frequency of oscillation.

$$f_{d2} = \frac{1}{4} f_n = \frac{1}{4} \times 7.053 = 1.7632 \text{ kHz}$$

$$f_{d2} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{1}{4C^2R^2}} \quad \text{i.e.} \quad \therefore \quad (2\pi f_{d2})^2 = \frac{1}{LC} - \frac{1}{4C^2R^2}$$

$$\frac{1}{4C^2R^2} = \frac{1}{LC} - (2\pi f_{d2})^2 = \frac{1}{(0.02546)(0.02 \times 10^{-6})} - (2\pi \times 1.7632 \times 10^3)^2$$

$$R^2 = \frac{1}{4C^2 \times 1841066564} \quad \text{i.e.} \quad R = \sqrt{\frac{1}{4 \times (0.02 \times 10^{-6})^2 \times 1841066564}}$$

$$\therefore \quad R = 582.65\ \Omega$$

Review Questions

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1. *With neat sketch explain resistance switching.*

AU : Dec.-04, Marks 6, May-05, Marks 9, Dec.-07, May-13, 18, Marks 8, Dec.-11, 12, 15, 17, Marks 4

2. *Derive an expression for restriking voltage when breaker has resistance R having value less than infinity. Discuss restriking voltage when breaker resistance is less than* $\frac{1}{2}\sqrt{\frac{L}{C}}$.

AU : May-06, Marks 16, Dec.-06, Marks 8

3. *In a system of 132 kV the circuit phase to ground capacitance is 0.01 mF, the series inductance is 6 H. Calculate the voltage appearing across the pole of a circuit breakers if a current of 10 A (instantaneous) is interrupted. Calculate value of the resistance to be used across contact space to eliminate the restriking voltage transient.* **(Ans. : 245 kV ; 12.25 kΩ)**

4. *Derive the expression to find the critical values of resistance to be connected across the circuit breaker contacts.* **AU : Dec.-18, Marks 13**

7.16 Arc Extinction

AU : Dec.-06,07,08,10,11, May-13

The electric discharge which is taking place between the electrodes is nothing but the electric arc. We have seen that when contacts of circuit breakers are separated, an arc is established between the contacts which will last for some period. The circuit breaker should be capable of extinguishing this arc without damaging. The behaviour of circuit breaker is greatly influenced by the arc.

Interruption of arc in case of d.c. circuits is much more difficult than that in case of a.c. circuits. In a.c. currents the natural current zero point is available where the arc vanishes and prevented from restriking.

The arc extinction in case of circuit breakers is not taking place frequently but still it produces lot of stress on the breaker. The different methods adopted for the arc extinction can be grouped into following three categories,

7.16.1 High Resistance Interruption

In this technique the resistance of current path is increased rapidly so that voltage drop is increased. The arc gets extinguished when the system voltage is insufficient to maintain the arc due to high voltage drop. This is normally used in d.c. circuit breakers and air break type a.c. circuit breakers having low capacity. The system inductance stores the energy which is dissipated in the arc.

7.16.2 Low Resistance or Current Zero Interruption

This method is used only in case of a.c. circuit breakers. At the natural current zero point of a.c. wave, the arc is interrupted and is prevented from restriking though there is high restriking voltage by increasing the dielectric strength of the contact gap. This method is used in high power a.c. circuit breakers.

7.16.3 Artificial Current Zero Interruption

In HVDC systems this method is employed for breaking d.c. currents where current is made zero artificially.

Review Question

1. *What are the different are interruption methods ? Explain any one in detail.*

AU : Dec.-06, Marks 3, Dec.-07, 08, 10, Marks 8, Dec.-11, May-13, Marks 10

7.17 Ionization of Gases

The non-ionized gas is generally a good dielectric medium. But the ionized gas is a conductor as it contains free electrons. In circuit breakers the contact space is ionized by following ways.

7.17.1 Thermal Ionization

At normal temperatures, molecules of gas are moving at various velocities in various directions and possess K.E. as $\frac{1}{2}$ mv^2. With increase in temperature the molecules break up in simpler form and then to atoms. At high temperature more and more collision takes place which will produce free electrons thus produces the ionization by heat and called thermal ionization.

7.17.2 Ionization by Collision

Any particle may be atom, molecule or electron at higher velocity may strike another particle so that the energy of moving particle is imparted to other one. This energy is sufficient to remove electrons from atoms. This is called ionization by collision.

7.17.3 Thermal Emission from Surface of Contacts

Whenever contacts of a breaker are closed, they are pressed against each other at high pressure. With the contacts separation the pressure between them reduces so true area of contact is decreased to a few spots on the surface. Due to this, high current density areas are produced which will cause high local temperature. Due to this, thermal emission takes place at contact surface.

7.17.4 Secondary Emission at Contact Surface

Under the influence of strong electric field between the contacts the electrons move from one contact to other producing emission from contact surface.

7.17.5 Field Emission

The voltage gradient at the contact surface is high which is sufficient to remove electrons from surface of electrodes since as contacts separate initially voltage gradient is very high which causes breakdown of gas. This is called field emission.

7.17.6 Photoemission

The electron emission from contact surface due to incident of light energy is called photoemission.

Review Question

1. *How contact space in circuit breakers is ionized ?*

7.18 Deionization

In circuit breakers the deionization is an important process as it supports arc extinction. This can be discussed in short as follows.

7.18.1 Recombination

If a gas contains positive ions and electrons then there is tendency between them to combine and form a neutral atom. This is called recombination. This will assist arc extinction as combination of positive ions and negative charges takes place inside.

7.18.2 Diffusion

The electrons from highly ionized space diffuse to the surrounding weakly ionized space which is an important process in building up dielectric strength.

7.18.3 Conduction of Heat

This will make the temperature to reduce and will help recombination. Particles at high temperature travel to the space at lower temperature. Thus kinetic energy is removed from the space which is ionized between the contacts.

Review Question

1. *What is the phenomenon of deionization in case of breakers ?*

7.19 Arc Formation

As seen earlier the separation of contacts of circuit breaker results in high local temperature on the contact surface. The contact surface get ionized due to thermal emission and the electrons are emitted. The space between the contacts is ionized and becomes conducting. Thus the arc is initiated between the contacts.

The Fig. 7.19.1 shows general form of arc voltage and arc current. It can be seen that voltage is nearly constant when current is nearly at its maximum.

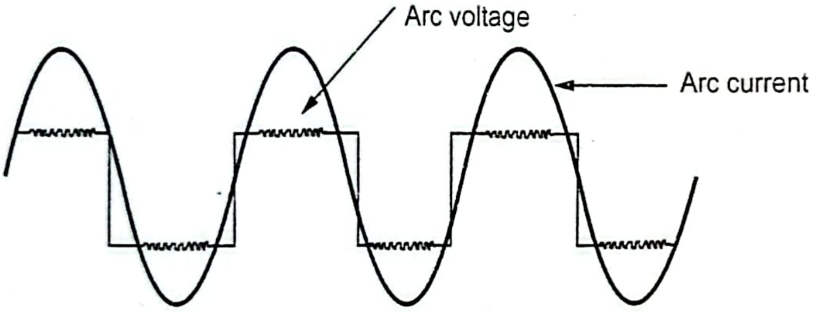

Fig. 7.19.1

The arc path is purely resistive and the arc voltage is in phase with an arc current. When the contacts are separated the arc voltage increases due to increase in arc length. The arc voltage is increased till it becomes more than system voltage across the contacts where arc gets extinguished.

7.20 High Resistance Arc Interruption Methods

AU : May-14

The various methods of high resistance and interruption are,

1. Lengthening the arc 2. Splitting of arc 3. Cooling of arc

7.20.1 Lengthening the Arc

In this method the arc length is increased by using arc runners which are horn like blades of conducting material. The arc runners are connected to arcing contacts and it is in the shape of letter 'V'. The arc is initiated at the bottom and blows upwards due to electromagnetic force. Due to this arc length increases and consequently arc is extinguished.

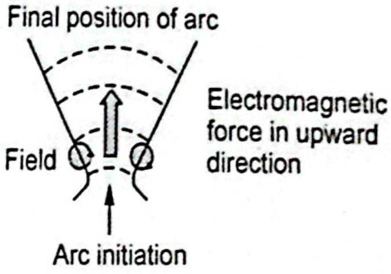
Final position of arc
Electromagnetic force in upward direction
Field
Arc initiation

Fig. 7.20.1 Arc lengthening

7.20.2 Splitting of Arc

In this method elongation of arc is done and the arc is split using arc splitters which are specially made plates of resin bonded fibre glass. These plates are placed in perpendicular path to arc so that it will be pulled towards it by electromagnetic force. When the arc is pulled upwards it gets elongated then split and cooled due to which it gets extinguished. This is shown in the Fig. 7.20.2.

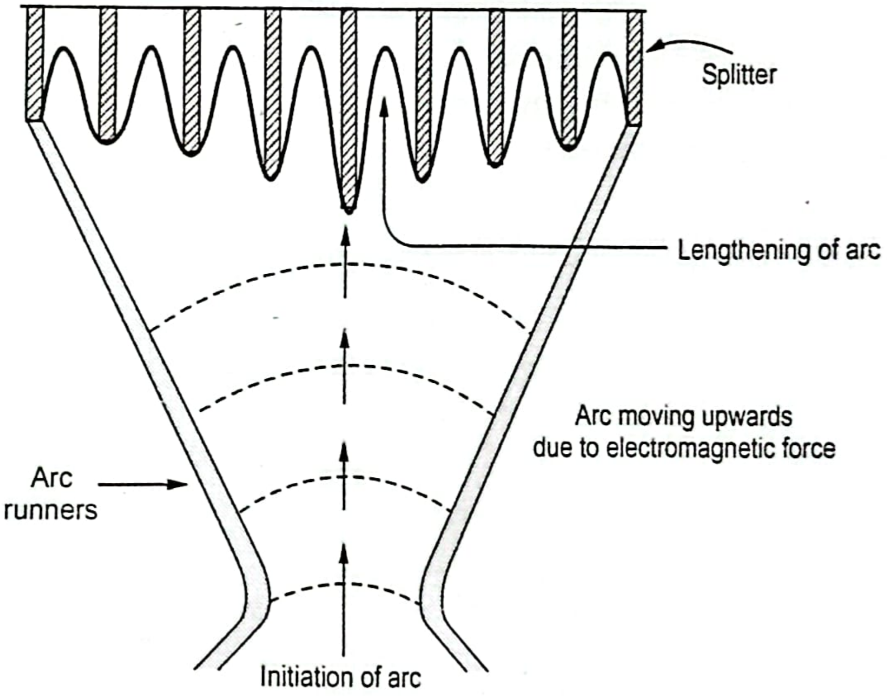
Splitter
Lengthening of arc
Arc moving upwards due to electromagnetic force
Arc runners
Initiation of arc

Fig. 7.20.2 Arc splitting

7.20.3 Cooling of Arc

As already seen, the recombination of ionized particles can be done by cooling the arc which removes heat from the arc. This is done by bringing the arc in contact with cooled air. Due to cooling the arc diameter reduces which will increase its resistance. This will help in arc extinction.

Review Questions

1. *Discuss in detail the various high resistance arc interruption methods.*
2. *Explain the physics of arc phenomena and interruption.* **AU : May-14, Marks 8**

7.21 Low Resistance or Zero Point Extinction

This method is used in a.c. arc interruption. The current becomes zero two times in a cycle. So at each current zero point the arc vanishes for small instant and again it appears.

But in a.c. circuit breakers the arc is interrupted at a current zero point. The space between the contacts is deionized quickly if there is fresh unionized medium such as oil or fresh air or SF_6 gas between the contacts at current zero point. This will make dielectric strength of the contact space to increase such that arc will be interrupted and discontinued after current zero. This action produces high voltage across the contacts which is sufficient to reestablish the arc. Thus the dielectric strength must be build more than the restriking voltage for faithful interruption of arc. Then the arc is extinguished at next current zero.

While designing the circuit breakers the care is taken so as to remove the hot gases from the contact space immediately after the arc. So that it can be filled by fresh dielectric medium having high dielectric strength.

In summary we can say that the arc extinction process is divided in thee parts,

a) Arcing phase b) Current zero phase c) Post arc phase

In arcing phase, the temperature of the contact space is increased due to the arc. The heat produced must be removed quickly by providing radial and axial flow to gases. The arc cannot be broken abruptly but its diameter can be reduced by the passage of gas over the arc. When a.c. current wave is near its zero, the diameter of the arc is very less and consequently arc is extinguished. This is nothing but current zero phase. Now in order to avoid the reestablishment of arc, the contact space must be filled with dielectric medium having high dielectric strength. This is post arc phase in which hot gases are removed and fresh dielectric medium is introduced.

Review Question

1. *Explain in brief low resistance or zero point extinction.*

7.22 Arc Interruption Theories

AU : May-11, 15, Dec.-12,14

There are two main theories explaining current zero interruption of arc

1) Recovery Rate Theory or Slepian's Theory

2) Energy balance theory or Cassie's Theory

7.22.1 Slepian's Theory

Slepian described the process as a race between the dielectric strength and restriking voltage. After every current zero, there is a column of residual ionized gas. This may cause arc to strike again by developing necessary restriking voltage and this voltage stress is sufficient to detach electrons out of their atomic orbits which releases great heat.

So in this theory rate at which positive ions and electrons recombine to form neutral molecules is compared with rate of rise of restriking voltage. Due to recombination dielectric strength of gap gets recovered. So rate of recovery of dielectric strength is compared with rate of rise of restriking voltage.

If the restriking voltage rises more rapidly than the dielectric strength, gap space breaks down and arc strikes again and persists.

In the Fig. 7.22.1,

a) Rate of dielectric strength is more than restriking voltage.

b) Rate of dielectric strength is less than rate of rise of restriking voltage.

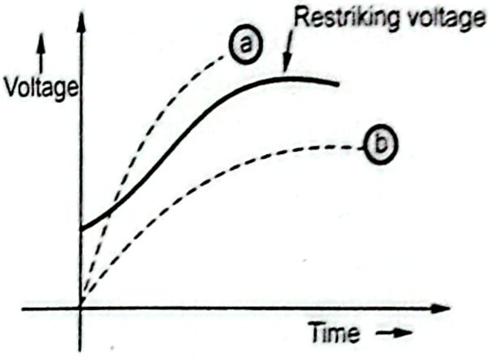

Fig. 7.22.1

The assumption made while developing this theory is that the restriking voltage and rise of dielectric strength are comparable quantities which is not quite correct. The second drawback is that the theory does not consider the energy relations in the arc extinction. The arcing phase is not covered by this theory so it is incomplete.

7.22.2 Cassie's Theory

Alternative explanation of above process is afforded by Cassie's theory or also called Energy balance theory.

Cassie suggested that the reestablishment of arc or interruption of an arc both are energy balance process. If the energy input to an arc continues to increase, the arc restrikes and if not, arc gets interrupted.

The theory makes the following assumptions :

a) Arc consists of a cylindrical column having uniform temperature at its cross section. The energy distributed in the column is uniform.

b) The temperature remains constant.

c) The cross-section of the arc adjusts itself to accomodate the arc current.

d) Power dissipation is proportional to cross sectional area of arc column.

The energy equation as expressed by Cassie is given by,

$$\frac{dQ}{dt} = EI - N$$

where Q = Energy content/length of arc in cm

E = Volts/cm

I = Total current

N = Total power loss/cm

Breakdown occurs if power fed to the arc is more than power loss. The theory is true for high currents.

Immediately after current zero, contact space contains ionized gas and therefore has a finite post zero resistance.

Now there is rising restriking voltage. This rising restriking voltage causes a current to flow between the contacts. Due to this current flow, power gets dissipated as heat in the contact space of circuit breaker.

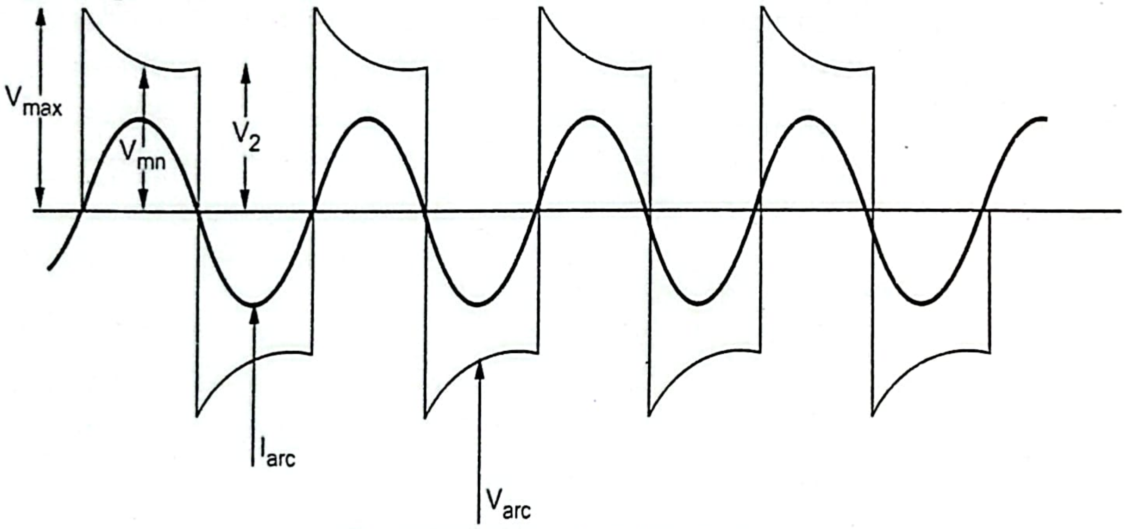

Fig. 7.22.2 Waveform of a.c. arc

Initially when restriking voltage is zero, automatically current and hence power is zero. It is again zero when the space has become fully deionize and resistance between the contacts is infinitely high. In between these two extreme limits, power dissipated rises to a maximum. If the heat so generated exceeds the rate at which heat can be removed from contact space, ionization will persist and breakdown will occur, giving an arc for another half cycle.

Review Question

1. *Discuss the recovery rate theory and energy balance theory of arc interruption in a.c. circuit breaker.* **AU : May-11, 15, Dec.-12, 14, Marks 16**

7.23 Auto Reclosing

The faults on transmission lines are of three categories,

1. Transient
2. Semi-permanent
3. Permanent

The transient faults are caused by lightening and temporary contacts with foreign objects. A small branch of tree falling on the line is a semi-permanent fault. The breaking of conductors is an example of permanent fault. Out of total faults 80 to 90 % faults are transient type. The transient faults are very frequent in power systems and occur for short period of time. Such faults do not damage the system permanently. If the system is isolated momentarily till arc gets extinguished, such faults disappear. Then the system can be restored to the normal operation by reclosing the contacts. For the permanent faults, such reclosing is not useful, as faults remain after reclosing. Practically in such cases double or triple shot reclosing is used if fault persists after the first trip. Such reclosing is done automatically now a days and called auto reclosing. Such a fault clearing and reclosing requires operation of many switchgear elements sequentially and it requires logical design principles as well.

7.23.1 Definitions Related to Auto Reclosing

The various definitions related to auto reclosing are,

1. **Relay Operating Time :** The time required for relay to operate after fault occurs.

2. **Circuit Breaker Operating Time :** The time required for fault arc to vanish from the energizing of relay coil.

3. **Circuit Breaker Dead Time :** The time between fault arc being extinguished and the making of circuit breaker contacts.

4. **Auto Reclose Relay Dead Time :** The time between the auto reclose system being energized and the closing of the circuit to the circuit breaker closing contacter.

5. **Closing Impulse Time of Auto Reclose Relay :** The time required for the closing contacts on auto reclose relay to close

6. **Reclaim Time of Auto Reclose Relay :** The time from the closing of contacts on the auto reclose relay to the completion of another circuit within the auto reclose scheme which will reset the scheme or lock out the scheme.

7. **Reclosing Time :** The time required by the circuit breaker to open and reclose the line and is measured form the instant of energization of trip circuit to the instant when the circuit breaker remakes the circuit.

8. Lockout of Circuit Breaker : Once the auto reclosing sequence is completed but unsuccessfully then further auto reclosing should not occur. So there is scheme to avoid this called lockout of circuit breaker. Once it is lock out, then manual reclosing is necessary.

9. Lockout of Auto Reclose Relay : It is a scheme which prevents further automatic reclosing irrespective of whether earlier sequence is executed successfully or unsuccessfully.

10. Antipumping : It is the feature which comes into the play when fault is permanent and it prevents repeated operation of the circuit breaker when impulse time is more than sum of the operating times of relay and the circuit breaker.

11. Number of Shots : It is the number of times the auto reclose scheme attempts to reclose, before locking out takes place. This number is adjustable or fixed.

12. Spring Winding Time : It is the time required by the motor to fully charge the spring after a closing operation.

13. Operation Counter : It is a cyclometer type dial which is operated electro magnetically and used to record the operations of the circuit breaker. This is useful from the maintenance point of view.

14. Counting Relay : This is an electro magnetic type relay using ratchet arrangement which is operated one step in forward direction when coil is energized.

The selection of these parameters depends on,

1. Type of protection.
2. Type of switchgear.
3. Possible stability problems.
4. Effects on the various types of consumer loads.

Review Questions

1. *Explain auto reclosing*
2. *Define the following terms*

   i) Relay operating time ii) Circuit breaker operating time iii) Reclosing time iv) Lockout of circuit breaker v) Antipumping.

7.24 Two Marks Questions with Answers

Q.1 State the two theories that are used to describe the arc extinction phenomenon.

Ans. : The two theories that are used to describe the arc extinction phenomenon

i. Recovery rate theory or Slepian's Theory

ii. Energy balance theory or Cassie's Theory

Q.2 Define the term current chopping.

Ans. : There are certain circumstances like disconnecting transformers on no load in which it is necessary to interrupt small inductive currents. The no-load current of a transformer is almost at zero power factor lagging. This current is normally smaller than the normal current rating of the breaker. Interrupting such current causes severe duty on the circuit breaker. This phenomenon is called current chopping.

Q.3 What are the two factors on which RRRV depends upon ?

Ans. : The two factors on which RRRV depends upon

i. Em which is peak value of recovery voltage (phase to neutral) in volts

ii. Values of inductance and capacitance in the circuit

Q.4 Draw the circuit breaker timing diagram, starting from the instant of fault to the instant of circuit breaker reclosing.

Ans. : Refer Fig. 7.6.2.

Q.5 Draw static and dynamic arc characteristics.

Ans. : When a graph of instantaneous values of voltage between the electrodes of a arc against corresponding values of current then it gives arc characteristics. If current changes rapidly with time, the characteristics are known as dynamic characteristics while if current changes slowly or if the rate of change of current is small then the characteristics are static. They are as shown in the Fig. 7.24.1.

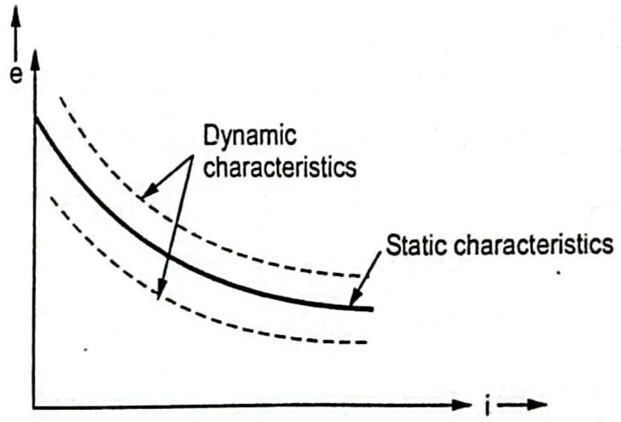

Fig. 7.24.1

Q.6 What is the effect of current asymmetry on the instantaneous values of recovery voltage ?

Ans. : When current wave is asymmetrical then the instantaneous value of the recovery voltage at current zero varies. The existance of large d.c. component in a short circuit current may cause the recovery voltage wave to start near the zero point instead of at its crest. The instantaneous value of recovery voltage is thus considerably reduced. This is shown in the Fig. 7.24.2.

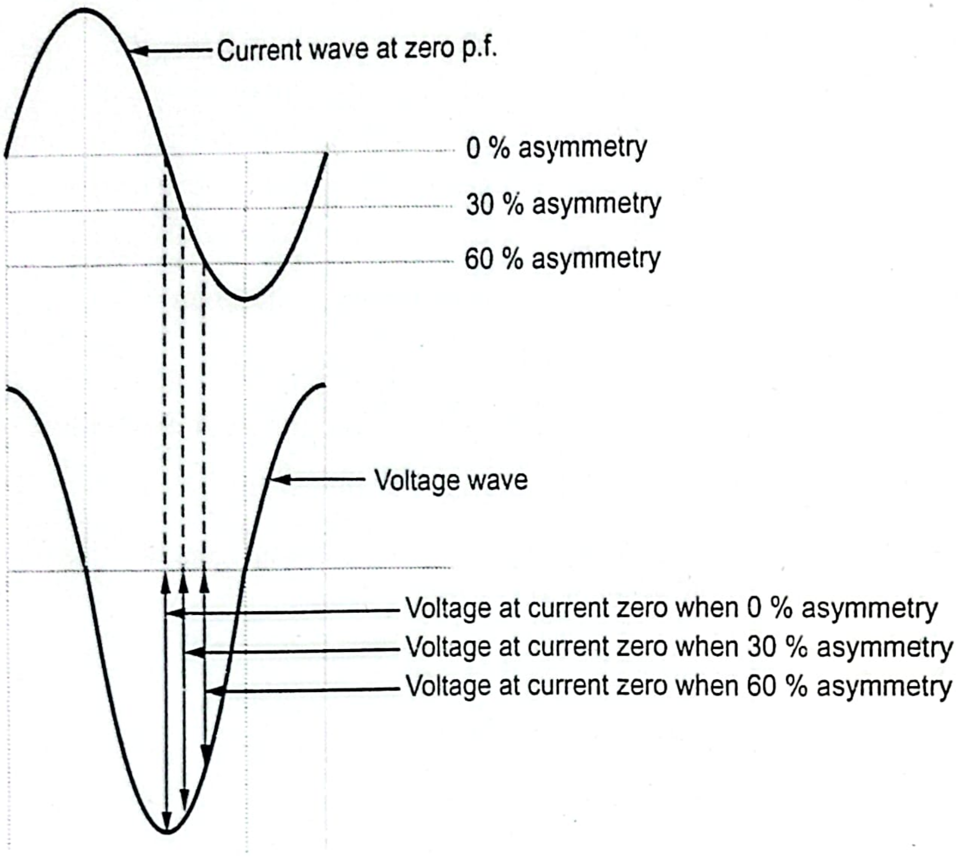

Fig. 7.24.2

Q.7 Mention different methods of high resistance arc interruption.

Ans. : The different methods of high resistance arc interruption are

i. Lengthening the arc

ii. Splitting of arc

iii. Cooling of arc

Q.8 Differentiate ac and dc circuit breaking. **AU : Dec.-16, May-22**

Ans. :

Sr. No.	AC circuit breaking	DC circuit breaking
1.	Current is reduced to zero twice in every cycle in AC circuits	Current is never reduced to zero as it is constant in DC circuits.
2.	Arc current can be reduced to zero when voltage is reduced to zero	Arc is continued and arc current is difficult to reduce unless the contacts are widely open
3.	The breakers can have higher rating for same capacity	The breakers can have lesser rating for same capacity due to larger arc currents
4.	Arc current naturally reduces to zero	Arc current is forced to zero
5.	Smaller voltages appear across breaker contacts during arc interruption	Larger voltages appear across breaker contacts during arc interruption

Q.9 What is meant by current chopping with respect to circuit breaking ?

AU : Dec.-14, May-19

Ans. : When low inductive currents, such as magnetizing current of transformer, shunt reactors are interrupted by breaker, there is rapid deionization of contact space and may cause the interruption of current before its neutral zero. This phenomenon is called current chopping.

Q.10 Define active recovery voltage and restriking voltage of a circuit breaker.

AU : May-17

Ans. : Active recovery voltage is defined as the instantaneous recovery voltage appearing at the instant of arc extinction.

A high frequency transient voltage appears across the breaker contacts which tries to restrike the arc. This voltage which is responsible for restriking of an arc is known as transient recovery voltage or restriking voltage.

Q.11 Define recovery voltage. **AU : May-13**

Ans. : The power frequency system voltage that appears between circuit breaker contacts after the extinction of an arc is called recovery voltage.

Q.12 Define rate of rise of restriking voltage. **AU : May-15**

Ans. : A high frequency transient voltage appears across the breaker contacts which tries to restrike the arc. The change in restriking voltage with time is known as rate of rise of restriking voltage (RRRV). If e is restriking voltage in volts then RRRV is given as,

$$\text{RRRV} = \frac{de}{dt} \text{ volts}/\mu \text{ sec}$$

Q.13 Define peak restriking voltage.

Ans. : The maximum instantaneous value attained by the restriking voltage is called the peak restriking voltage.

Q.14 List the factors on which the arc resistance depends. **AU : May-18**

Ans. : The arc resistance depends on following factors

a) **Degree of ionization :** If there are less number of ionized particles between the contacts then the arc resistance increases.

b) **Length of arc :** The arc resistance is a function of length of arc which is nothing but separation between the contacts. More the length, more is the arc resistance.

c) **Cross-section of arc :** If the area of cross-section of the arc is less then arc resistance is large.

Q.15 What are the problems encountered in d.c. circuit breaking ?

Ans. : The 2 basic problems in d.c. circuit breaking are,

i) The natural zero current does not occur as in case of a.c. circuit breakers.

ii) The amount of energy to be dissipated during short interval of breaking is very high as compared to conventional a.c. circuit breakers.

Q.16 What is meant by arc interruption in circuit breakers ?

Ans. : Whenever the contacts of circuit breaker are opened, the circuit is not braked immediately as heavy arc is drawn between the contacts which will continue for some time. This arc should be extinguished at the earliest. The events taking place during opening of circuit breaker contacts and final extinction of arc refers to arc interruption in circuit breakers.

Q.17 What are the problems encountered in the interruption of capacitive currents ?

Ans. : The problems encountered in the interruption of capacitive currents are

i. Possibility of repeated restriking of arc

ii. Large oscillations can take place

iii. Large energy stored in capacitor needs to be dissipated

iv. Possibility of occurrence of severe voltage transients

v. Due to pre arcing during closing of breaker on capacitive load arc may struck between the contacts before they close which might damage the contacts.

Q.18 List the factors affecting the transient recovery voltage.

Ans. : The transient recovery voltage depends on

i) Circuit parameters such as inductance and capacitance

ii) Fault current level

iii) System grounding

iv) Internal factors of circuit breakers like the first pole to clear a fault

v) Bushing capacitance of circuit breakers

vi) The type of the switching duty involved.

Q.19 What is the principle involved in High Resistance Interruption ?

Ans. : In this technique the resistance of current path is increased rapidly so that voltage drop is increased. The arc gets extinguished when the system voltage is insufficient to maintain the arc due to high voltage drop. This is normally used in d.c. circuit breakers and air break type a.c. circuit breakers having low capacity. The system inductance stores the energy which is dissipated in the arc.

Q.20 Write the effects of arc resistance.

Ans. : With large resistance of arc, the current flowing will be smaller and it will be helpful for the arc extinction. With small resistance of arc, the current flowing will be large causing large power loss, heating of contacts and its wear and tear resulting in damage.

Q.21 List out the various methods of arc interruption. **AU : May-15**

Ans. : The various methods of arc interruption are

i. High resistance interruption

a. Lengthening the arc b. Splitting of arc c. Cooling of arc

ii. Low resistance or current zero interruption

iii. Artificial current zero interruption

Q.22 Distinguish between recovery voltage and restriking voltage. **AU : Dec.-16**

Ans. :

Sr. No.	Recovery voltage	Restriking voltage
1.	The power frequency system voltage that appears between circuit breaker contacts after the extinction of an arc is called recovery voltage.	A high frequency transient voltage appears across the breaker contacts which tries to restrike the arc. This voltage which is responsible for restriking of an arc is known as transient recovery voltage or restriking voltage.
2.	It is the voltage that appears in steady state conditions	It is the voltage that appears during transient conditions.
3.	The frequency of this voltage is having normal power frequency value	The frequency of this voltage does not have normal power frequency value but often variable
4.	It is the voltage that appears across breaker contacts after contacts separation and extinction of arc.	It may appear across the breaker contacts if its rate of rise is higher than rate of building of dielectric strength of the contact space.

Q.23 Write the inference of resistance switching. **AU : Dec.-13**

Ans. : It can be seen that the interruption of low inductive currents, interruption of capacitive currents give rise to severe voltage oscillations. These excessive voltage surges during circuit interruption can be prevented by the use of shunt resistance R across the circuit breaker contacts. This process is known as resistance switching.

When the resistance is connected across the arc, a part of the arc current flows through the resistance. This will lead to decrease in arc current and increase in rate of deionization of the arc path and resistance of arc. This will increase current through shunt resistance. This process continues until the current through the arc is diverted through the resistance either completely or in major part. If the small value of the current remains in the arc then the path becomes so unstable that it is easily extinguished.

Q.24 **V_1, V_2, V_3 be the peak to peak value of the R,Y,B phase voltage waves immediately after the arc extinction from an oscillogram. What may be the average recovery voltage (line to line) for the CB ?**

Ans. : The average recovery voltage (line to line) for the CB is given by,

$$\text{Average recovery voltage} = \frac{\sqrt{3}\,V}{2\sqrt{2}} = 0.61\text{ V} \quad \text{where } V = V_1 = V_2 = V_3$$

Q.25 **How do you quench an arc in a circuit breaker ?** **AU : May-14**

Ans. : The arc quenching is carried out in circuit breaker by high resistance and low resistance methods.

Q.26 **What are the demerits of resistance switching ?** **AU : May-14**

Ans. : The demerits of resistance switching are -

i) Value of resistor to be connected is critical as low value is required for reducing transient recovery voltage while relatively higher value is required for voltage equalization.

ii) Switching circuitary is required for automatic connection of resistance.

Q.27 **State the Slepian theory for arc interruption.** (Section 7.22.1) **AU : Dec.-17**

Q.28 **Why the rate of rise of restriking voltage plays important role in circuit breaker operation ?** **AU : Dec. - 18**

Ans. : It is the rate at which the restriking voltage rises. It is responsible for restriking of arc. It plays an important role because if it is smaller than the rate at which the dielectric between the contacts is developed then only the arc gets extinguished.

Q.29 **Which factors the ARC phenomenon depends upon ?** **AU : Dec.-22**

Ans. : The factors affecting are phenomenon,

i) Degree of ionization

ii) Length of arc

iii) Cross-section of arc

7.25 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *Derive the expression for restriking voltage and maximum RRRV.* **[Section 7.12]** **[8]**

Q.2 *Explain the phenomenon of interruption of capacitive current in a circuit breaker.* **[Section 7.13]** **[8]**

May-17

Q.3 *Write short notes on :*
i) Current chopping. **[Section 7.14]**
ii) Interruption of capacitive current. **[Section 7.13]** **[16]**

Dec.-17

Q.4 *Write short notes on :*
i) Current chopping. **[Section 7.14]**
ii) Resistance switching. **[Section 7.15]** **[16]**

May-18

Q.5 *With neat sketch explain resistance switching.* **[Section 7.15]** **[8]**

Q.6 *Explain current chopping with suitable diagrams.* **[Section 7.14]** **[8]**

Dec.-18

Q.7 *Derive the expression to find the critical values of resistance to be connected across the circuit breaker contacts.* **[Section 7.15]** **[13]**

May-19

Q.8 *Explain the various arc interruption methods.* **[Sections 7.13 and 7.14]** **[13]**

Q.9 *Describe the operating principle of DC circuit breaker.* **[Section 7.3]** **[13]**

(Regulation 2017)

May-22

Q.10 *Explain the phenomenon of current chopping in a circuit breaker and list the methods to reduce the same.* **[Section 7.14]** **[13]**

❑❑❑

UNIT V

8 Circuit Breakers

Syllabus

Types of circuit breakers - air blast, oil, SF_6 and vacuum circuit breakers - comparison of different circuit breakers - HVDC Breaker.

Contents

8.1	Introduction		
8.2	Requirements of Circuit Breaker		
8.3	Basic Action of a Circuit Breaker		
8.4	Classification of Circuit Breakers		
8.5	Air Blast Circuit Breakers	**Dec.-04,17,18,** **May-05,07,11,15,17,19,22,**	Marks 16
8.6	Air Break Circuit Breaker	**Dec.-13,**	Marks 8
8.7	Sulphur Hexafluoride (SF_6) Circuit Breaker	**Dec.-05,07,12,14,15,22,** **May-06,07,12,14,15,**	Marks 16
8.8	Miniature Circuit Breaker (MCB)		
8.9	Moulded Case Circuit Breaker (MCCB)		
8.10	Vacuum Circuit Breakers	**May-04,05,06,11,15,17,18,** **Dec.-10,16,**	Marks 10
8.11	Oil Circuit Breakers	**May-04,06,11,**	Marks 8
8.12	Low Oil or Minimum Oil Circuit Breaker	**Dec.-06,08,10,11,15,22,** **May-06,13,**	Marks 16
8.13	HVDC Circuit Breaker	**Dec.-06, 07,**	Marks 8
8.14	Selection of Circuit Breaker	**Dec.-08,12,**	Marks 8
8.15	Circuit Breaker Ratings	**May-06,12, Dec.-11,15,**	Marks 10
8.16	Type Tests		
8.17	Routine Tests		
8.18	Development Tests		
8.19	Reliability Tests		
8.20	Commissioning Tests		
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8.22	Short Circuit Test Layout		
8.23	Indirect Testing	**May-07, Dec.-14**	Marks 16
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8.25	Two Marks Questions with Answers		
8.26	University Questions with Answers (Long Answered Questions)		

8.1 Introduction

As already seen in the last chapter, whenever any fault occurs in the power system then that part of the system must be isolated from the remaining healthy part of the system. This function is accomplished by circuit breakers. Thus a circuit breaker will make or break a circuit either manually or automatically under different conditions such as no load, full load or short circuit. Thus it proves to be an effective device for switching and protection of different parts of a power system.

In earlier days fuse was included in the protective system. But due to some limitations they are not used in practice nowadays. The main difference between a fuse and circuit breaker is that under fault condition the fuse melts and it is to be replaced whereas the circuit breaker can close or break the circuit without replacement.

Thus a circuit breaker is defined as a switching and current interrupting device in a switchgear which serves the purpose of switching during normal operating conditions for the purpose of operation and maintenance and switching during abnormal conditions and interrupting the fault currents.

Review Question

1. *What do you mean by a circuit breaker ?*

8.2 Requirements of Circuit Breaker

The power associated with the circuit breakers is large and it forms the link between the consumers and suppliers. The necessary requirements of circuit breakers are as follows,

1. The normal working current and the short circuit current must be safely interrupted by the circuit breaker.
2. The faulty section of the system must be isolated by circuit breaker as quickly as possible keeping minimum delay.
3. It should not operate with flow of overcurrent during healthy conditions.
4. The faulty circuit only must be isolated without affecting the healthy one.

Review Question

1. *What are the requirements of circuit breaker ?*

8.3 Basic Action of a Circuit Breaker

The Fig. 8.3.1 shows the elementary diagram of a circuit breaker. It consists of two contacts a fixed contact and a moving contact. A handle is attached at the end of the moving contact. It can be operated manually or automatically. The automatic operation needs a separate mechanism which consists of a trip coil. The trip coil is energized by secondary of the current transformer. The terminals of circuit breaker are brought to power supply.

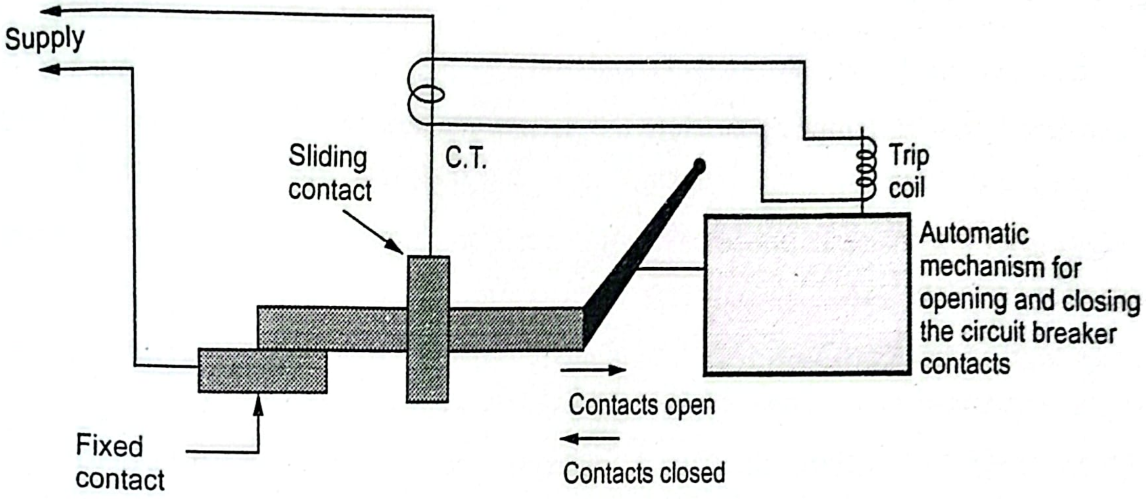


Fig. 8.3.1 Basic action of circuit breaker

Under normal working conditions the e.m.f. produced in the secondary winding of the transformer is insufficient to energize the trip coil completely for its operation. Thus the contacts remain in closed position carrying the normal working current. The contacts can be opened manually also by the handle.

Under abnormal or faulty conditions high current in the primary winding of the current transformer induces sufficiently high e.m.f. in the secondary winding so that the trip coil is energized. This will start opening motion of the contacts. This action will not be instantaneous as there is always a time lag between the energization of the trip circuit and the actual opening of the contacts. The contacts are moved towards right away from fixed contact.

As we have seen already the separation of contacts will not lead to breaking or interruption of circuit as an arc is struck between the contacts. The production of arc delays the current interruption and in addition to this it produces large amount of heat which may damage the system or the breaker. Thus it becomes necessary to extinguish the arc as early as possible in minimum time, so that heat produced will lie within the allowable limit. This will also ensure that the mechanical stresses produced on the parts of circuit breaker are less.

The time interval which is passed in between the energization of the trip coil to the instant of contact separation is called the **opening time**. It is dependent on fault current level.

The time interval from the contact separation to the extinction of arc is called **arcing time**. It depends not only on fault current but also on availability of voltage for maintenance of arc and mechanism used for extinction of arc.

Review Question

1. *Explain the basic action of circuit breaker.*

8.4 Classification of Circuit Breakers

The circuit breakers are classified in various ways as,

According to the interrupting medium the circuit breakers are classified as air circuit breaker, air blast circuit breaker, oil circuit breaker and magnetic blast circuit breaker.

According to service there are two types of circuit breakers viz indoor circuit breaker and outdoor circuit breaker.

Depending on the operation, the types of circuit breakers are gravity opened, gravity closed and horizontal break circuit breaker.

On the basis of action, the circuit breakers are classified as automatic and non-automatic circuit breaker.

According to method of control, the circuit breaker may be controlled directly or it may be operated remotely. The remote control may be manual, pneumatic or electrical.

The way of mounting classifies the circuit breakers into panel mounted, rear of panel or remote from panel type.

Depending on the tank construction, the circuit breakers are classified as separate tank for each pole type or one tank for all poles type.

On the basis of contacts, the different types of circuit breakers are Butt, Wedge, Laminated flat contact, Explosion chamber etc.

Out of the various ways of classification of circuit breakers the general way of classification is on the basis of medium used for arc extinction which is normally oil, air, Sulphur Hexa Flouride (SF_6) or vacuum.

Review Question

1. *Explain the classification circuit breakers based on various factors.*

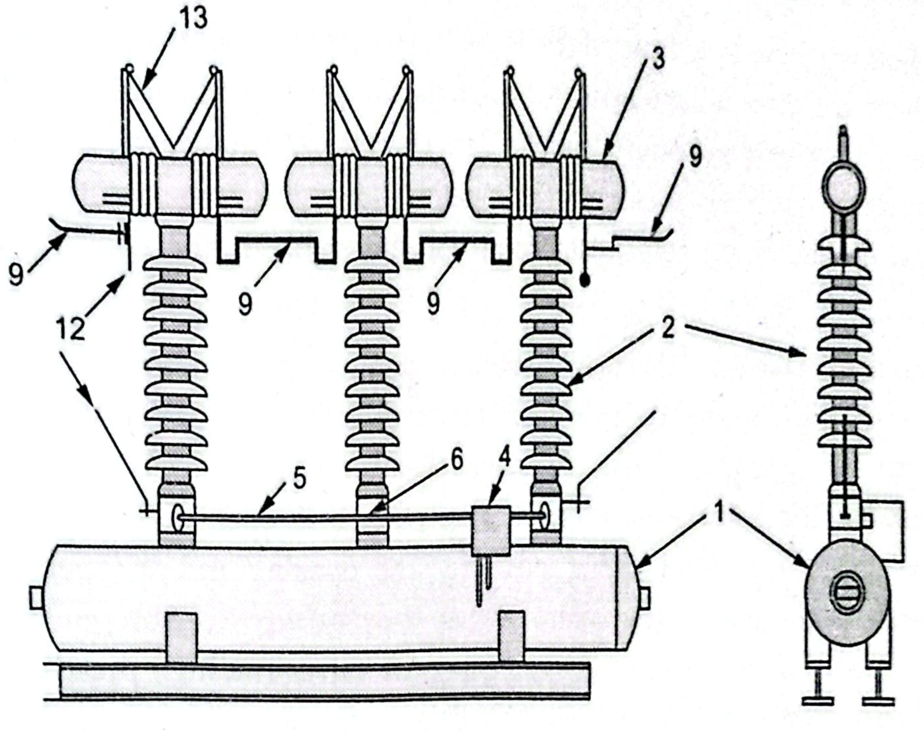
8.5 Air Blast Circuit Breakers

AU : Dec.-04,17,18, May-05,07,11,15,17,19,22

These type of circuit breakers were employed in earlier days for voltages ranging from 11 to 1100 kV. At high voltages this type of circuit breakers are most suitable. In this type of circuit breakers the compressed air is used for the arc extinction. Hence it is called **compressed air** circuit breaker.

8.5.1 Construction of an Air Blast Circuit Breaker

The Fig. 8.5.1 shows the constructional details of air blast circuit breaker.

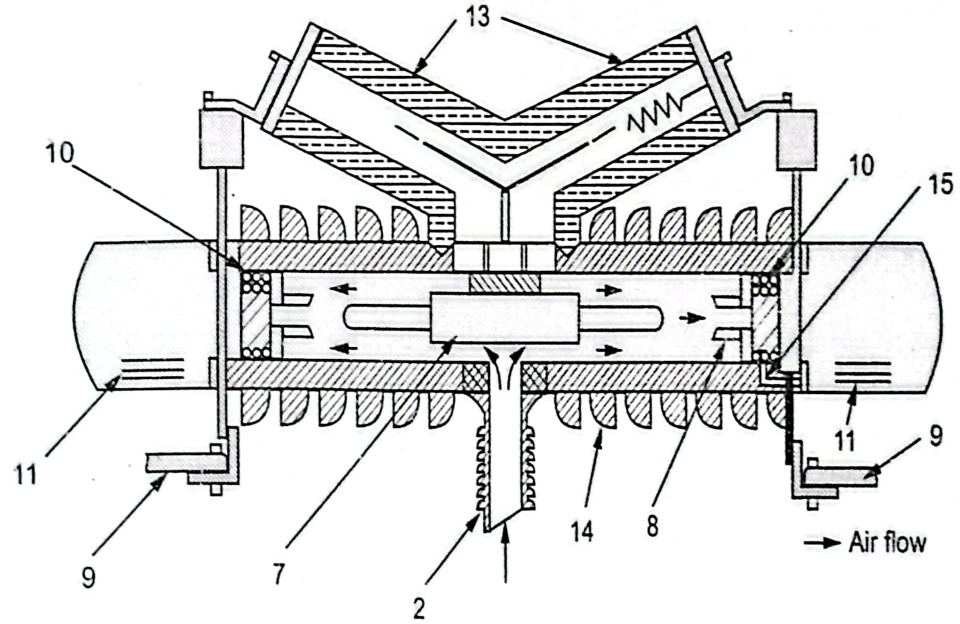


ELEVATION

END-VIEW

One pole of an extra high voltage air blast circuit-breaker

Fig. 8.5.1 (a)



Details of double arc extinction chamber

1. Tank air reservior (receiver)
2. Hollow insulator assembly
3. Double arc extinction chamber
4. Pneumatic operating mechanism
5. Operating rod
6. Pneumatic valve
7. Fixed contact (in 3)
8. Moving contact (in 3)
9. Connection for current
10. Compression springs
11. Openings for air outler
12. Arcing horns optional
13. Resistance switching unit
14. Enclosure
15. Port

Fig. 8.5.1 (b) Construction of air blast circuit breaker

At the bottom there is a tank which is called air reservoir with the valves. On this reservoir there are three hollow insulator columns. On the top of each insulator column there is double arc extinguishing chamber. The current carrying parts are connected to the arc extinction chambers in series. The assembly of entire arc extinction chamber is mounted on insulators as there exists large voltage between the conductors and air reservoir.

The double arc extinction chamber is shown separately in the Fig. 8.5.1 (b). It can be seen that for each circuit breaker pole there are six breaks as there are three double arc extinction poles in series. Each arc extinction chamber consists of two fixed and two moving contacts. These contacts can move axially so as to open or close. The position depends on air pressure and spring pressure. The opening rod is operated by the opening mechanism when it gets control signal (may be electrical or pneumatic). This will lead to flow of high pressure air by opening the valve. The high pressure air enters the double arc extinction chamber rapidly. Due to the flow of air the pressure on moving contacts increases than spring pressure and contacts open. The contacts travel through a small distance against the spring pressure. Due to the motion of moving contacts the port for outgoing air is closed and the whole arc extinction chamber is filled with high pressure air. But during the arcing period the air passes through the openings shown and takes away ionized air of arc. In case of making operation the valve is turned which connects hollow column of insulator and the reservoir. The air is passed to the atmosphere due to which pressure of air in the chamber is dropped to atmospheric pressure and closing of moving contacts is achieved against spring pressure.

8.5.2 Working

An auxiliary compressed air system is required by this type of circuit breaker. This will supply air to the air reservior of the breaker. During the opening operation, the air is allowed to enter in the extinction chamber which pushes away moving contacts. The contacts are separated and the blast of air will take ionized gases with it and helps in extinguishing the arc. This will require only one or two cycles. There are two major types - cross blast and axial blast.

In cross blast type, the blast of air cuts across the arc. It is less frequently used in the practice. In axial blast type, the blast of air is along the arc. This type of design is common in use.

8.5.2.1 Cross Blast Type

The Fig. 8.5.2 shows the schematic arrangement of a cross blast type.

The flow of air is across the arc. The moving contact is near to the arc splitter assembly. The air blast forces the arc on to the arc splitter plates. These plates will lengthen the arc. Depending upon the breaking capacity of the breaker, the size and

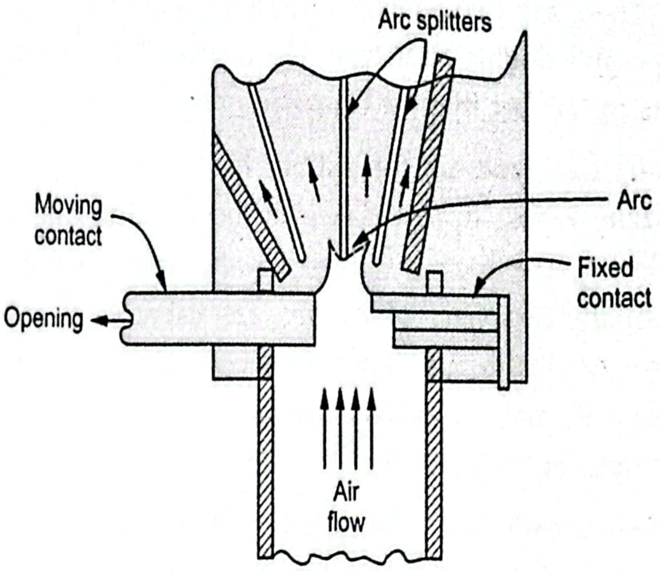
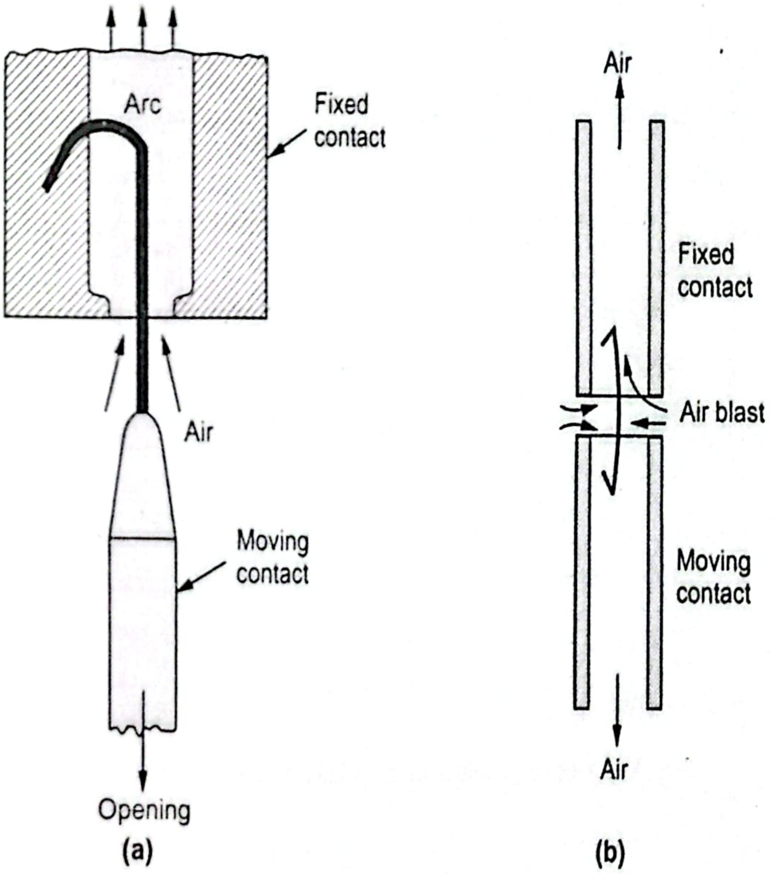

Arc splitters
Moving contact
Arc
Fixed contact
Opening
Air flow

Fig. 8.5.2 Cross blast type circuit breaker

number of plates are decided. The fixed contact is mounted at the base between the two insulating blocks. It consists of a number of silver surfaced spring loaded copper fingers. The arcing portion is surfaced with a silver tungsten alloy. The moving contact consists of flat copper silver faced blade. Resistance switching is not required as sufficient resistance is automatically introduced in the arc to control the restriking transient. The cross blast breakers are commonly used in indoor circuit breakers of medium high voltage class.

8.5.2.2 Axial Blast Type

In this type the flow of blast of air is along the line of arc. This is shown in the Fig. 8.5.3.


Arc
Fixed contact
Air
Moving contact
Opening
Air
Fixed contact
Air blast
Moving contact
Air

(a) (b)

Fig. 8.5.3 Axial blast type circuit breaker

There are two subtypes which are shown in the Fig. 8.5.3 (a) and (b) viz single blast type and double blast type. The double blast arrangement is also called radial blast type due to the fact that the blast flows radially into the space between the contacts.

In this type air flows from high pressure reservior to the atmosphere through a nozzle. Whose design makes air to expand in the low pressure zone. It will attain high velocity. The high speed air flowing axially along the arc will cause removal of heat from the periphery of the arc. The diameter of arc reduces to a low value at current zero. At this instant of the arc interruption the contact space is filled with the fresh air. This will make possible to remove the hot gases and fast building up of the dielectric strength of the medium.

As already seen during the contact closing, the air from the extinction chamber is allowed to pass to the atmosphere. This will reduce the pressure on the moving contacts and will assist the closing operation. The total operation is represented in the Fig. 8.5.4.

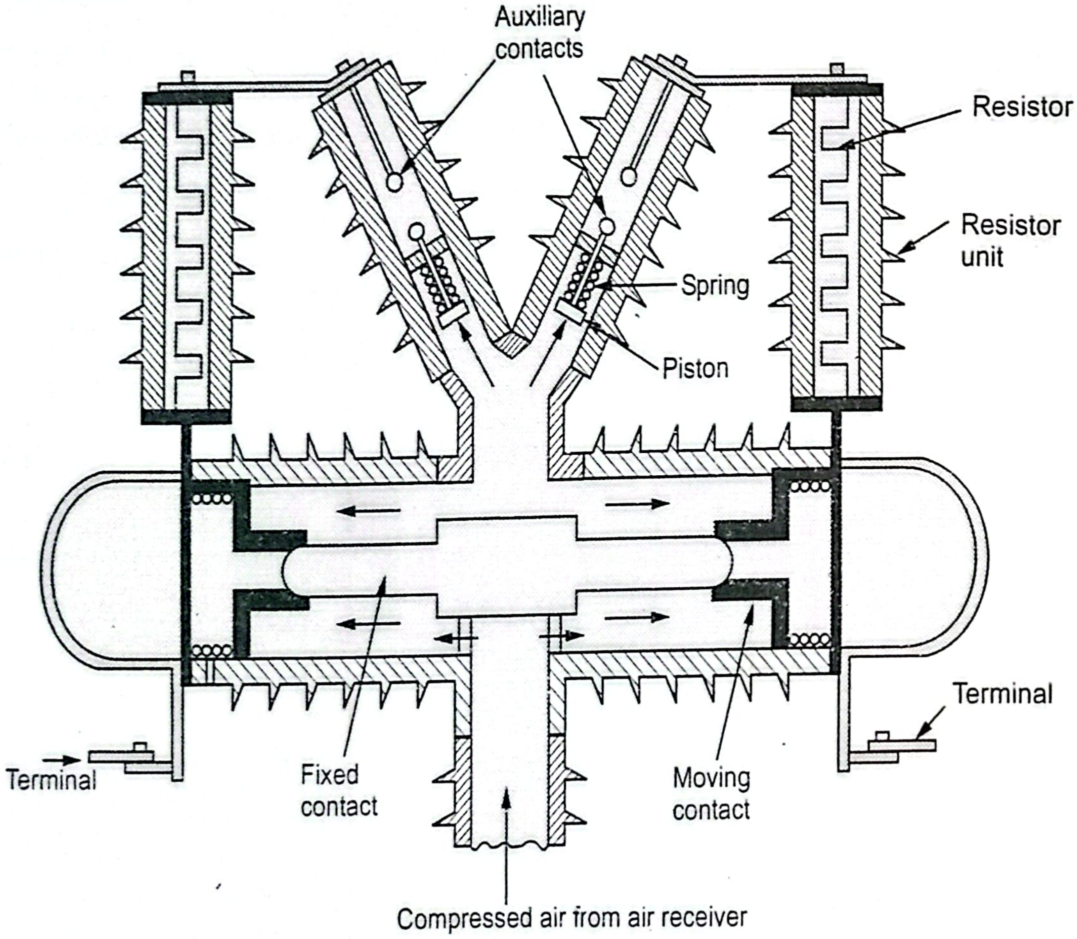

Auxiliary contacts
Resistor
Resistor unit
Spring
Piston
Terminal
Terminal
Fixed contact
Moving contact
Compressed air from air receiver

Fig. 8.5.4 Modification in air blast circuit breaker

In air blast circuit breaker, the pressure generated in the extinction chamber is independent of arc current and the circuit breaker is said to be of external energy source. The air pressure in this type of breaker is constant which is sufficient enough to break the rated breaking current. In this type of circuit breakers the breaking capacity is found by pressure of extinguishing medium.

For low values of currents, the arcing time does not change appreaciably since air pressure is independent of arc current. For breaking low current, high pressure air will be required. Due to this the current gets chopped before reaching natural zero. This will give rise to high restriking voltage and the contact space is likely to break down. Therefore these high voltages must be allowed to discharge to avoid breakdown of insulation of circuit breaker. Thus resistance switching is commonly employed in these breakers.

After the current zero, the contact sapce resistance is large as the space between the contacts is filled with high pressure air having high dielectric strength. The high restriking voltage that appears across the contacts does not damp out through the contact gap as resistance of contact gap after current zero is high. The magnitude of voltage that appears across the contacts is very large

The Fig. 8.5.4 shows the modified arrangement for a double arc extinguishing chamber. The auxiliary contacts are located in the inclined V shaped insulators while the resistors are located in the vertical insulators. When the contacts are separated, air flows in the arc extinguishing chamber. The main contacts are separated while auxiliary contacts are pushed to close due to which resistors are connected across the arc for a short time of arcing.

After the extinction of the arc, the pressure on either side of the auxiliary contacts is adjusted in such a way that, the auxiliary contacts open and resistor circuit is interrupted. Ceramic resistances of non-linear characteristics are used for resistance switching.

With high current, the non-linear resistor offers low resistance. Due to this, the arc current is diverted through the resistor unit. With reduction in arc current, the resistance of non-linear resistor increases which causes a large voltage drop across the resistor units. The voltage available for the arc between the auxiliary contacts is insufficient and the arc between the auxiliary contacts is automatically extinguished.

8.5.3 Compressed Air System for Air Blast Circuit Breaker

The schematic arrangement shown in the Fig. 8.5.5 represents compressed air system.

The air reservoir in the air blast circuit breaker contains air of pressure of the order of 20-30 kg force/cm^2. This air pressure is maintained by these reservoirs for 4 to 12 repeated operations.

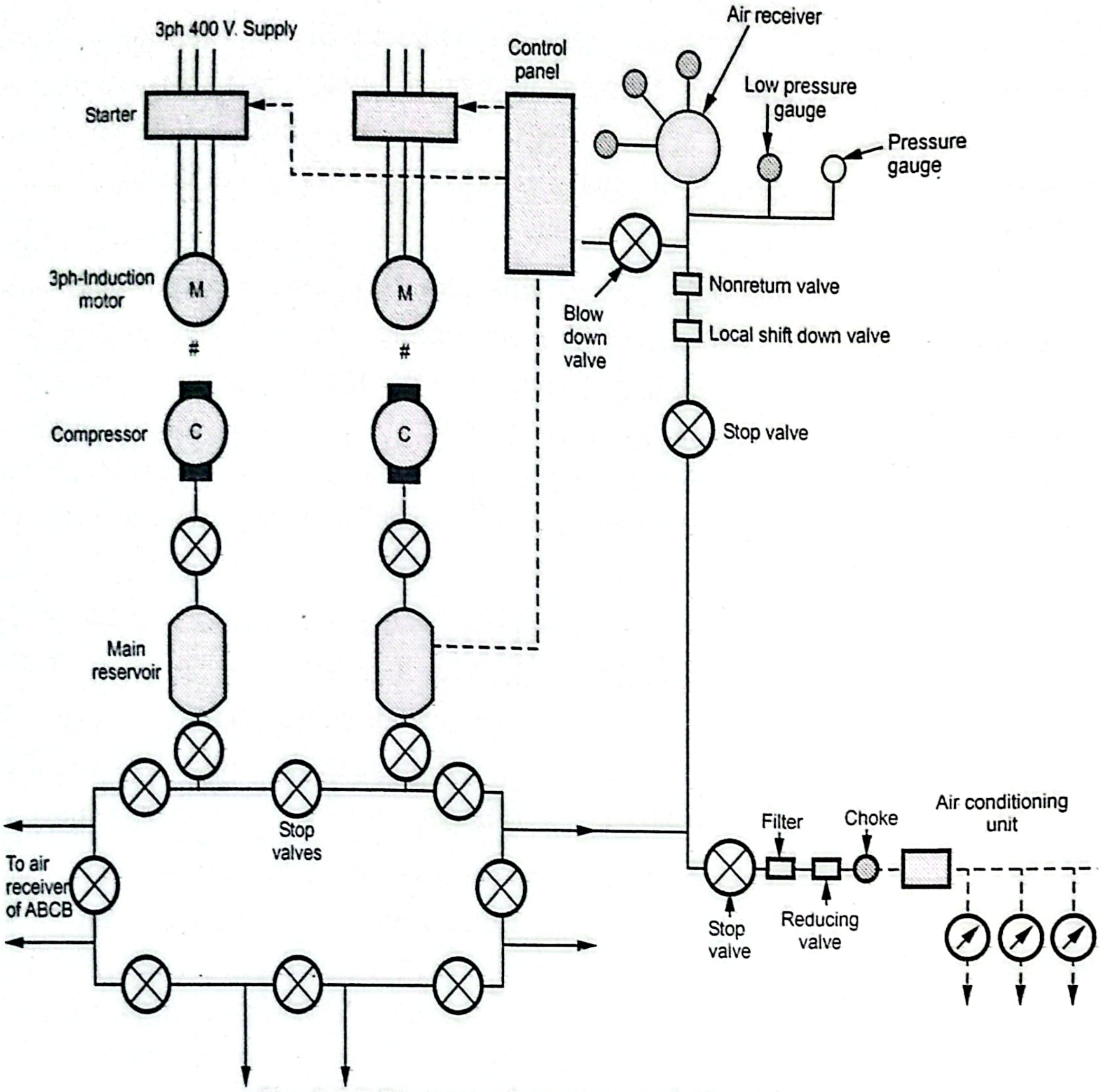

3ph 400 V. Supply
Starter
Control panel
Air receiver
Low pressure gauge
Pressure gauge
3ph-Induction motor
M
M
Blow down valve
Nonreturn valve
Local shift down valve
Compressor
C
C
Stop valve
Main reservoir
Stop valves
To air receiver of ABCB
Filter
Choke
Air conditioning unit
Stop valve
Reducing valve

Fig. 8.5.5 Diagram of compressed air system

When the pressure in the air reservoir of the circuit breaker reduces below a certain value say 20 kgf/cm^2, the pneumatic valve opens automatically and air is allowed to enter in the air reservoir from compressed air system at high pressure. The pressure in the air reservoir is then maintained at a desired value.

The size of compressor depends upon the number of circuit breakers, the number of makes and breaks expected and amount of air to be used in each make and break. The compressor feeds the air at high pressure into the main receiver through oil filters and water filters.

8.5.4 Advantages

The various advantages of air blast circuit breakers are,

i) No fire hazards are possible with this type of circuit breaker.

ii) The high speed operation is achieved.

iii) The time for which arc persists is short. Thus the arc gets extinguished early.

iv) As arc duration is short and consistent, the amount of heat released is less and the contact points are burnt to a less extent. So life of circuit breaker is increased.

v) The extinguishing medium in this type of circuit breaker is compressed air which is supplied fresh at each operation. The arc energy at each operation is less than that compared with oil circuit breaker. So air blast circuit breaker is most suitable where frequent operation is required.

vi) This type of circuit breaker is almost maintenance free.

vii) It provides facility of high speed reclosure.

viii) The stability of the system can be well maintained.

8.5.5 Disadvantages

The various disadvantages of air blast circuit breakers are,

i) If air blast circuit breaker is to be used for frequent operation it is necessary to have a compressor with sufficient capacity of high pressure air.

ii) The maintenance of compressor and other related equipments is required.

iii) There is possibility of air leakages at the pipe fittings.

iv) It is very sensitive to restriking voltage. Thus current chopping may occur which may be avoided by employing resistance switching.

8.5.6 Applications

The air blast circuit breakers are preferred for arc furnace duty and traction system because they are suitable for repeated duty. These type of circuit breakers are finding their best application in systems operating in range of 132 kV to 400 kV with breaking capacities upto 7000 MVA.

Review Questions

1. *Explain the working of air blast circuit breaker with reference to i) Axial blast ii) Cross blast.*

   AU : Dec.-18, May-22, Marks 13

2. *With a neat figure, explain the construction and working of air blast circuit breaker.*

   AU : May-05, 11, 15, 17, 19, Dec.-17, Marks 16

3. *With neat sketch, explain the principles of axial blast air circuit breaker.*

   AU : Dec.-04, Marks 8

4. *What are the advantages and disadvantages of air blast circuit breaker ?*

   AU : Dec.-04, May-07, Marks 8

8.6 Air Break Circuit Breaker

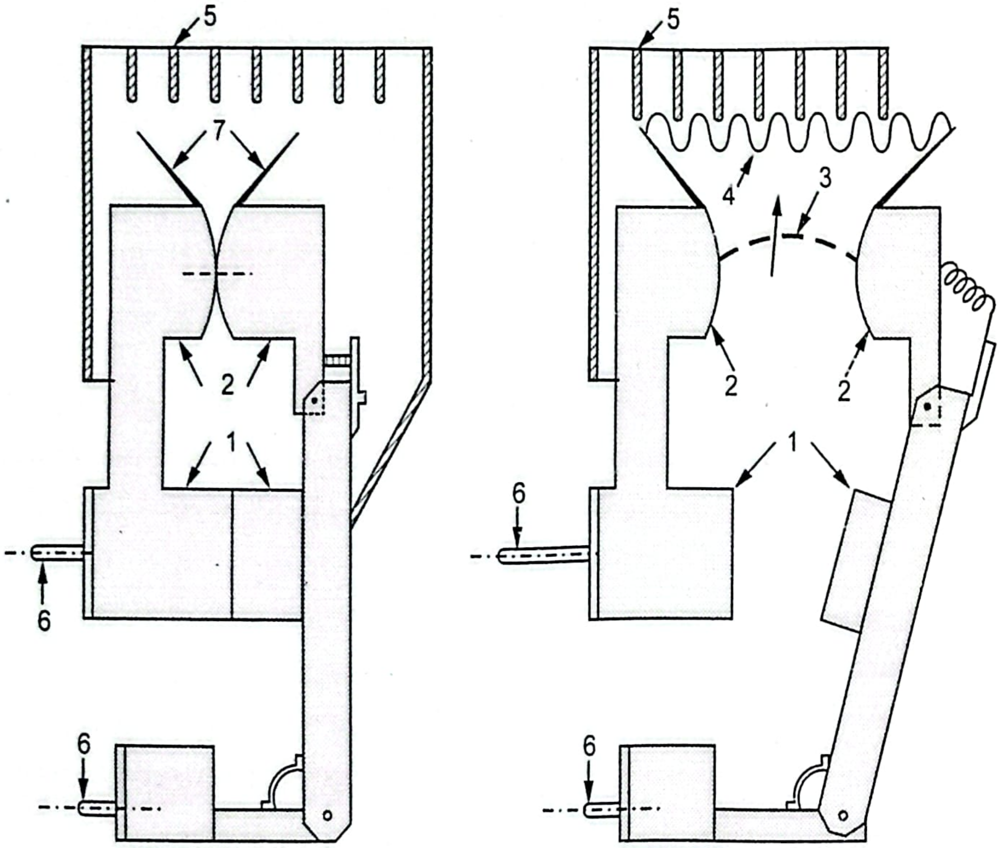
AU : Dec.-13

In air circuit breakers the atmospheric pressure air is used as an arc extinguishing medium. The principle of high resistance interruption is employed for such type of breakers. The length of the arc is increased using arc runners which will increase its resistance in such a way that the voltage drop across the arc becomes more than the supply voltage and the arc will be extinguished.

This type of circuit breaker is employed in both a.c. and d.c. type of circuits upto 12 kV. These are normally indoor type and installed on vertical panels. The lengthening of arc is done with the help of mangetic fields. Some typical ratings of this type of circuit breaker are 460 V - 3.3 kV with current range 400 - 3500 A or 6.6 kV with current range 400 - 2400 A etc.

8.6.1 Construction

The Fig. 8.6.1 shows the constructional details of air break circuit breaker.



(I) Contact closed

(II) Contacts open

Principle of air-break circuit-breaker

1. Main contacts
2. Arcing contacts
3. Arc rising in the direction of the arrow
4. Arc getting split
5. Arc splitter plates
6. Current carrying terminals
7. Arc runners

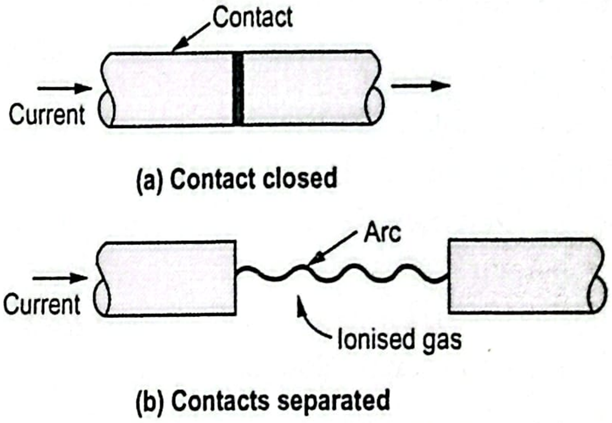
Fig. 8.6.1 Construction of air break circuit breaker

It consists of two sets of contacts.

1) Main contacts 2) Arcing contacts.

During the normal operation the main contacts are closed. They are having low resistance with silver plating. The arcing contacts are very hard, heat resistant. They are made up of copper alloy. Arc runners are provided at the one end of arcing contact. On the upper side arc splitter plates are provided.

8.6.2 Working



(a) Contact closed

(b) Contacts separated

Fig. 8.6.2 Working of air break circuit breaker

As seen from the Fig. 8.6.2 the contacts remain in closed position during normal condition. Whenever fault occurs, the tripping signal makes the circuit breaker contacts to open. The arc is drawn in between the contacts.

Whenever the arc is struck between the contacts, the surrounding air gets ionised. The arc is then cooled to reduce the diameter of arc core. While separating, the main contacts are separated first. The current is then shifted to arcing contains. Later on the arcing contacts also start separating and arc between them is forced upwards by the electromagnetic forces and thermal action. The arc travels through the arc runners. Further it moves upwards and split by arc splitter plates. Due to all this finally the arc gets extinguished as the resistance of the arc is increased.

Due to lengthening and cooling, arc resistance increases which will reduce the fault current and will not allow to reach at high value. The current zero points in the a.c. wave will help the arc extinction. With increase in arc resistance the drop across it will go on increasing.

Whenever arc leaves the contacts it is passed through arc runners with the help of blow out coils which provide a magnetic field due to which it will experience a force as given by electromagnetic theory ($F = BIl$). This force will assist in moving the arc upwards. The magnetic field produced is insufficient to extinguish the arc. For systems having low inductances arc gets extinguished before reaching extremity of runners because lengthening of arc will increase the voltage drop which is insufficient to maintain the arc.

For high inductance circuits if it is not extinguished while travelling through arc runners then it is passed through arc splitters where it is cooled. This will make the effective deionization by removing the heat from arc.

8.6.3 Applications

This type of circuit breakers are commonly employed for industrial switchgear, auxiliary swithgear in generating stations.

Review Questions

1. *Explain construction and working of air break circuit breaker.* **AU : Dec.-13, Marks 8**
2. *With neat sketch explain the working of air break circuit breaker.*

8.7 Sulphur Hexafluoride (SF_6) Circuit Breaker

AU : Dec.-05,07,12,14,15,22, May-06,07,12,14,15

Pure sulphur hexafluoride gas is inert and thermally stable. It is having good dielectric and arc extinguishing properties. It is also an electronegative gas and has strong tendency to absorb free electrons. SF_6 gas remains in gaseous state upto a temperature of 9 °C. Its density is about five times that of air and the free heat convection is 1.6 times as much as that of air. Also being inert it is non-inflamable, non-poisonous and odourless.

The contacts of the breaker are opened in a high pressure flow of SF_6 gas and an arc is struck between them. The conducting electrons from the arc are captured by the gas to form relatively immobile negative ions. The loss of this conducting electrons developes enough strength of insulation which will extinguish the arc. Thus SF_6 circuit breakers are found to be very effective for high power and high voltage service and widely used in electrical equipments. Only the care to be taken is that some by-products are produced due to breakdown of gas which are hazard to the health of the personnel and it should be properly disposed.

Several types of SF_6 circuit breakers are designed by various manufacturers in the world during the recent years which are rated for voltages from 3.6 to 760 kV.

The property of this gas is that the gas liquifies at certain low temperatures. The liquification temperature can be increased with pressure. This gas is commercially manufactured in many countries and now used extensively in electrical industry.

The gas is prepared by burning coarsely crushed roll sulphur in fluorine gas in a steel box. The box must be provided with staggered horizontal shelves each containing about 4 kg of sulphur. The steel box is gas tight. After the chemical reaction taking place in the box, the SF_6 gas obtained contains impurities in the form of fluorides such as S_2F_{10}, SF_4 etc. Thus it must be purified before it is supplied. The manufacturing of this gas at large scale reduces its cost.

The dielectric strength of SF_6 gas at any pressure is more than that of air. When the gas comes in contact with the electric arc for long period, the decomposition effects are small and dielectric strength is not considerably reduced and the metallic fluorides that are formed are good insulators and are not harmful to the breaker.

8.7.1 Properties of SF_6 Gas

The properties of SF_6 gas are divided as,

1. Physical properties 2. Chemical properties 3. Dielectric properties.

8.7.1.1 Physical Properties

i) The gas is colourless, odourless, non-toxic and nonharmful to health.

ii) The gas is non-inflammable.

iii) It is heavy gas having high density.

iv) Liquification starts at low temperatures which depends on pressure.

v) The heat transferability is high as compared to air at same pressure.

vi) The heat content property is much more which will assist cooling of arc after current zero.

vii) The gas is electronegative.

8.7.1.2 Chemical Properties

i) The gas is chemically inert and stable upto 500 °C. The life of metallic part, contacts is longer in SF_6 gas. The components do not get deteriorated. Hence the maintenance requirements are reduced.

ii) During arc extinction, SF_6 is decomposed to SF_4, SF_2. The products of decomposition are toxic and hence proper care must be taken for their disposal.

iii) The metallic fluorides are good dielectric materials. Hence are safe for electrical equipment.

8.7.1.3 Dielectric Properties

i) The dielectric strenght of SF_6 gas at atmospheric pressure is 2.9 times that of air and 30 % less than that of dielectric oil.

ii) At higher pressure, the dielectric strength of a gas increases. This is very much advantageous as smaller clearances and small size of components are required for same kV. The variation is shown in the Fig. 8.7.1.

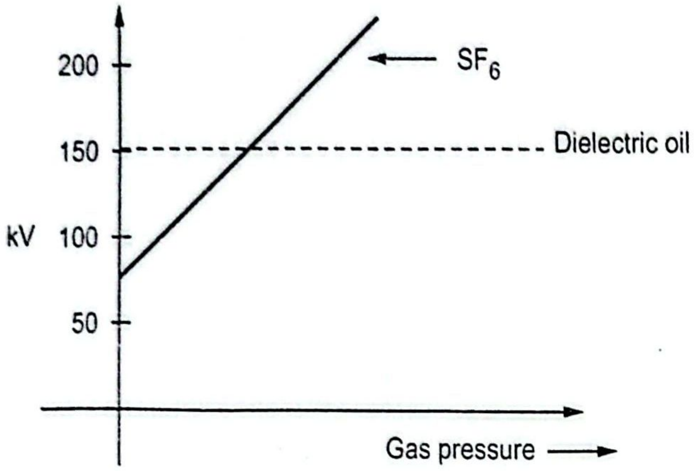


Fig. 8.7.1

iii) The breakdown voltage in SF_6 gas is a function of pressure. The gas follows the Paschen's law which is given as "In uniformly distributed electric field the breakdown voltage in a gas is directly proportional to the product of gas pressure and electrode gap". The parameters affecting breakdown voltage are electrode configuration, distribution of electric field, vicinity of insulating supports, moisture waveshapes are normally constant.

iv) If electric field is non-uniform the breakdown voltage against pressure curve does not obey Paschen's law. The variation is as shown in the Fig. 8.7.2.

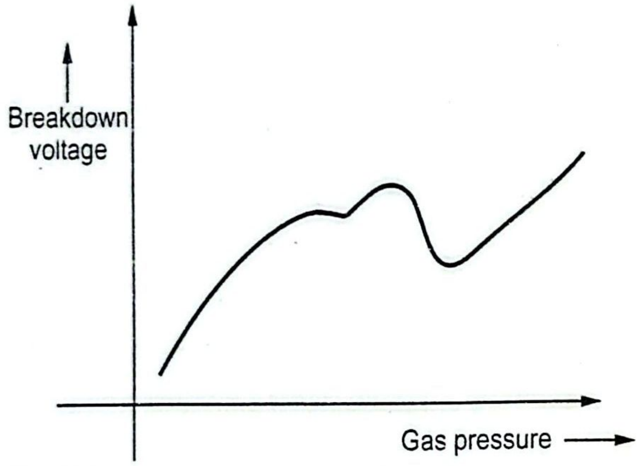


Fig. 8.7.2 The breakdown voltage increases with pressure

After 2.5 kgf/cm^2, the voltage starts reducing and then again increases. This pressure is called critical pressure. The dielectric strength at pressure between 2-3 kgf/cm^2 is high so it is preferred in this type of circuit breakers. However pressure of 5 kgf/cm^2 may also be selected for arc quenching purpose.

v) With rough electrode surface, breakdown voltage reduces as ionisation starts earlier near the sharp points. Hence the surface must be smooth.

vi) The breakdown can occur at low values provided that the insulator supports are covered by moisture and conducting dust, as flashover may take place along the surface of support insulators. Hence insulators must be extremely clean.

vii) The breakdown is initiated at sharp edges of conducting parts having maximum stress concentration. Good dielectric stress distribution is important.

viii) The breakdown value depends on the wave shape characterised by peak value, wave front, polarity in case of impulse wave etc. The breakdown voltages reduces with increase in steepness and increase in duration of wave.

ix) Even with dilution of SF_6 with air, its dielectric strength is not much affected. As already seen the gas is electronegative so arc time constant is lower which is nothing but the time required to regain dielectric strength by medium after final current zero. This time is of the order of few microseconds in this type of circuit breaker.

8.7.1.4 Electronegativity and Arc Time Constant

SF_6 is electronegative gas. Electronegativity is a chemical property which describes the tendency of an atom to attract electrons towards itself and thus the tendency to form negative ions. It is also measure of the tendency of an atom to attract a bonding pair of electrons.

Because of this electronegativity property, SF_6 gas has excellent insulating strength. When a free electron collides with the neutral gas molecule to form negative ion, the electron is absorbed by the neutral gas molecule. The negative ions formed are comparatively heavier than free electrons and hence under the influence of an electric field, the ions do not get sufficient energy to have cumulative ionization in the gas. Thus electrons from contact space are easily removed and electron avalanche breakdown is avoided. Hence SF_6 gas possesses excellent dielectric strength and has the property of rapid recombination after the arc initiating source is removed.

The electronegativity of SF_6 gas gives excellent dielectric and insulating properties due to which it is used as arc quenching medium in circuit breakers and switchgear.

The **time constant** of the medium is defined as the time between current zero instant and the instant the conductance of contact space reaches zero value. Even though the current reduces to zero, heat produced in the medium between the contacts of the circuit breaker is sufficient enough to ionize air or oil which will act as conductor and arc is struck between contacts. This arc should be extinguished as quickly as possible with low arc time constant.

Due to the electronegativity of SF_6 gas, the arc time constant of SF_6 gas is very low. The rate of rise of dielectric strength is also high. Thus SF_6 circuit breakers are suitable for switching conditions with large rate of rise of Transient Recovery Voltage (TRV).

8.7.2 Construction of Non-puffer Type SF_6 Breaker

The Fig. 8.7.3 shows the constructional details of SF_6 circuit breaker. It consists of arc interruption chamber wherein fixed and moving contacts are enclosed. The chamber is filled with SF_6 gas. The chamber is connected to a reservoir containing SF_6 gas.

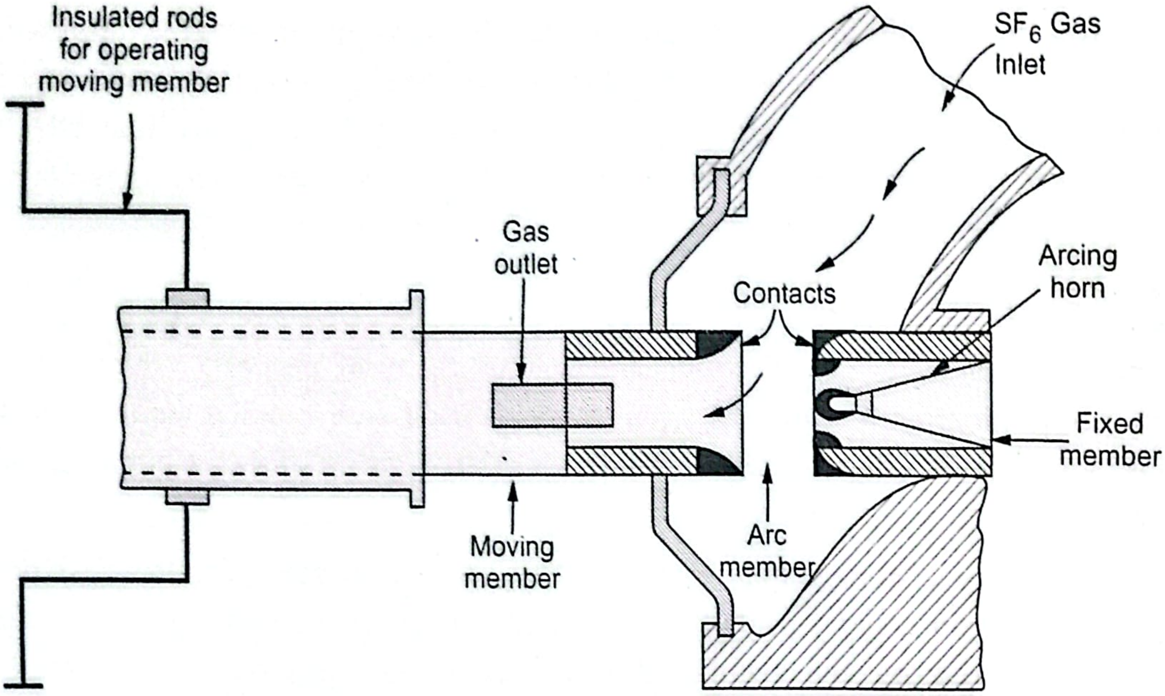


Fig. 8.7.3 Construction of SF_6 breaker

When the contacts of circuits breakers are opened, the valve mechanism allows high pressure SF_6 gas from the reservior to flow towards the arc interruption chamber. The fixed contact is a hollow, cylindrical current carrying contact fitted with arc horn. The moving contact is also hollow cylinder containing holes in the sides to permit SF_6 gas to pass through these holes after flowing across the arc. The tips of fixed and moving contacts are coated with copper tungsten arc resistant material. The gas is reconditioned and reused by suitable auxiliary system after each operation of the breaker.

8.7.2.1 Working

During the normal working conditions the contacts are in closed position which are surrounded by SF_6 gas at a pressure of about 2.8 kg/cm^2.

When the contacts are separated then arc is struck between them. The movement of moving contact and opening the valve are synchronized together which permits high pressure SF_6 gas from the reservoir to the arc interruption chamber. The high pressure gas absorbs free electrons in the arc path to form immobile negative ions. The gas also removes the heat from the arc. Due to this, arc diameter reduces and it becomes small during current zero with the turbulent flow around current zero, the arc is extinguished.

Due to electronegativity of SF_6 gas the medium between the contacts immediately builds up and causes extinction of arc. After the breaker operation the valve is closed by a set of springs.

In SF_6 breakers, the gas is made to flow from a high pressure zone to a low pressure zone through a convergent divergent nozzle. The flow of mass of gas is a function of nozzle throat diameter, the pressure ratio and time to flow. The gas flows axially along the arc length at very high speed which will take away heat from the arc causing the reduction in diameter of arc. Finally the arc diameter becomes very small at current zero and arc is extinguished. The contact space is filled by fresh SF_6 gas and dielectric strength of contact space is rapidly built due to electronegativity of SF_6 gas.

Consider the flow pattern shown in the Fig. 8.7.4. In earlier days puffer type circuit breakers were used with single flow pattern.

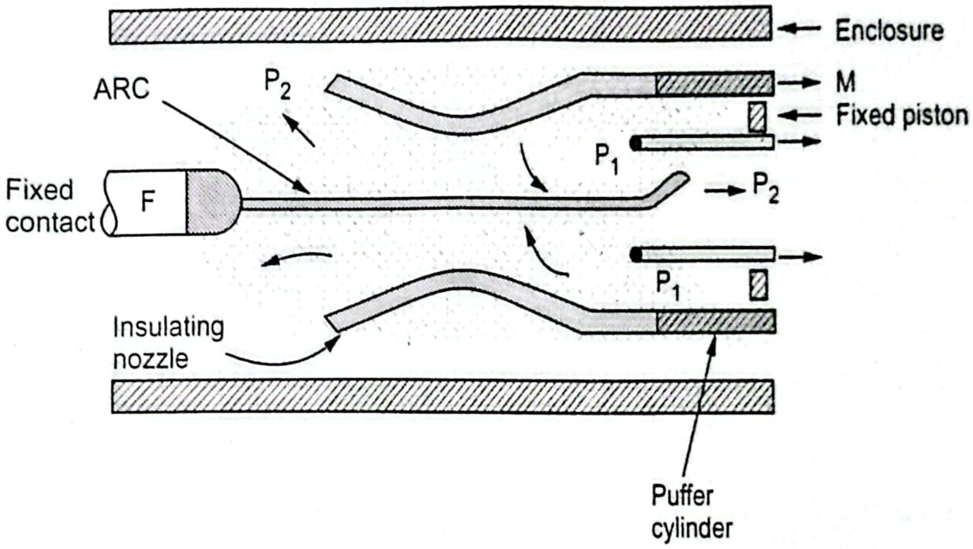


Fig. 8.7.4 Arc extinction in single pressure puffer type circuit breaker

The single flow pattern has limited quenching ability and is used for breaking currents. The four stages of puffer action explains arc quenching process in single flow puffer type circuit breaker.

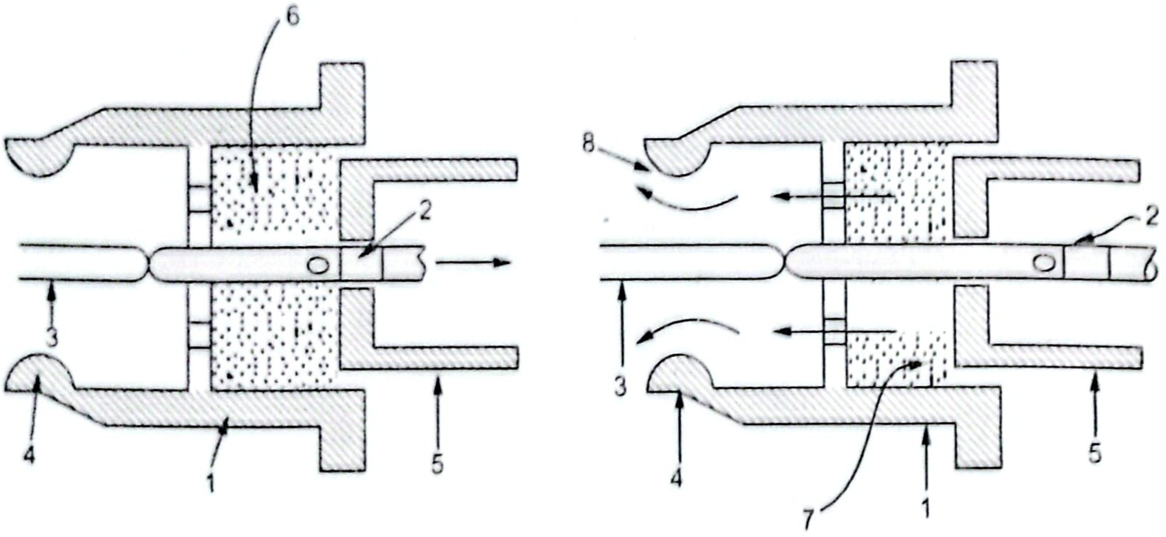
When breaker is fully closed, the pressure in puffer cylinder P_1 is equal to that of outside the cylinder. But during opening operation, puffer cylinder and moving contact tube start moving. Gas gets compressed withing puffer cylinder ($P_1 > P_2$). When contacts move further, arc is drawn. The compressed gas flows from higher pressure P_1 to lower pressure P_2 through the nozzle.

After further advancement the flow pattern was improved. The gas from puffer cylinder was allowed to flow in forward direction through nozzle and also in reverse direction through hollow contact tube.

Double flow removes the heat from the arc efficiently and causes lengthening of arc. It gives the breaking capacity one and half times more than that of single flow type. So nowadays double flow pattern is used in SF_6 circuit breakers.

8.7.3 Single Pressure Puffer Type SF_6 Circuit Breaker

It employs puffer principle explained earlier. The Fig. 8.7.5 shows principle of operation of single pressure puffer type SF_6 circuit breaker. The operating mechanism (1) is installed at base of the insulator and is linked with movable contact in the interrupter by means of insulating operating rod (4) and a link mechanism (5) The circuit breaker is filled with SF_6 gas at a pressure of about 5 kgf/cm^2. The breaking time obtained with puffer type breaker is nearly 3 cycles.



(a) Breaker fully closed

(b) Contacts separated

1. Moveable cylinder (Puffer Cylinder)
2. Moving contact
3. Fixed contact
4. Insulating nozzle
5. Fixed piston
6. Gas trapped in before compression
7. Compressed gas between 1 and 5
8. The arc being extinguished by puffer action

Fig. 8.7.5 Single pressure puffer type SF_6 breaker

In this case, gas is compressed by the moving cylinder system and is released through a nozzle while extinction of an arc.

The Fig. 8.7.5 (a) illustrates fully closed position of interrupter. Moving cylinder 1 is coupled with moving contact 2 against the fixed piston 5. As a result there is a relative motion between 1 and 5 and the gas is compressed in the cavity 6. This trapped gas is released through a nozzle hole, during arc extinction process. During the travel of moving contact 2 and movable cylinder 1 gas puffs over the arc and reduces arc diameter by axial convertion and radial dissipation. At current zero arc diameter becomes too small and arc gets extinguished.

The puffing action continues for sometime even after the arc extinction until the contact space is filled with cool and fresh gas.

8.7.4 Double Pressure Type SF_6 Circuit Breaker

In this type, gas from high pressure system is released into low pressure system through a nozzle during arc extinction process.

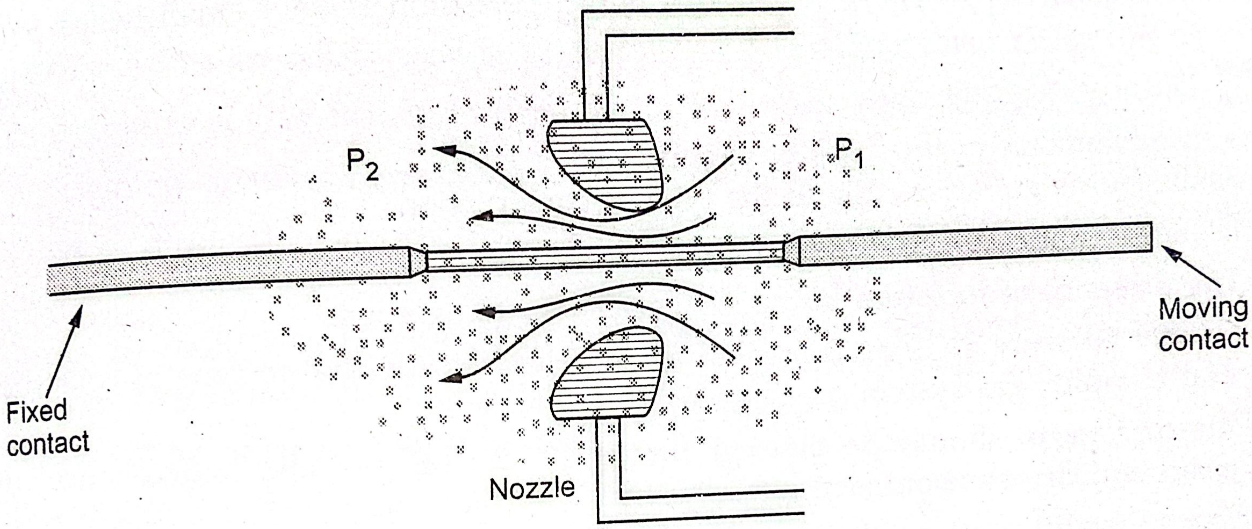


Fig. 8.7.6 Double pressure type SF_6 circuit breaker

In this circuit breaker gas is made to flow from zone P_1 to P_2 through a convergent divergent nozzle. The nozzle is located such that flow of gas covers the arc. Gas flow attains almost supersonic speed in divergent portion of nozzle, thereby gas takes away the heat from periphery of arc causing reduction in diameter of the arc. Finally arc diameter becomes almost zero at current zero and arc gets extinguished. Arc space is filled with fresh SF_6 gas which increases dielectric strength of contact space.

8.7.5 Advantages of SF_6 Circuit Breaker

The advantages of SF_6 circuit breaker are,

1. The size of SF_6 breaker is smaller than conventional circuit breaker of same rating.
2. SF_6 gas is noninflammable and chemically stable, decomposition products are not explosive hence no danger of fire.
3. Same gas is recirculated in the circuit hence requirement of gas is small.
4. Ample overload margin : For the same size of conductors, current carrying ability of SF_6 circuit breaker is about 1.5 times than that of air blast circuit breaker because of more heat transferability.
5. The breaker is silent in operation and does not make sound like air blast circuit breaker due to its closed gas circuit.

6. Sealed construction avoids contamination by moisture, dust etc. There are no carbon deposites.
7. Minimum maintenance required for this breaker. It requires light foundation and minimum auxiliary equipment.
8. Ability to interrupt low and high fault currents, magnetising currents, capacitive currents without excessive overvoltages with small arcing time.
9. Problems connected with current chopping are minimum.
10. No contact replacement required. Contact corrosion is very small hence contacts do not suffer oxidation.

8.7.6 Disadvantages

The disadvantages of this type of circuit breaker are,

1. Sealing problem arises due to the type of construction.
2. Imperfect joint lead to leakage of gas.
3. The presence of moisture in the system is very dangerous.
4. Double pressure SF_6 circuit breaker are relatively costly due to type of construction and complex gas system.
5. Internal parts should be cleaned throughly during periodic maintenance under clean and dry environment.
6. Special facilities are needed for transporting the gas, which is very costly.
7. SF_6 breakers are costly as there is high cost of SF_6 gas.
8. Since the gas is to be reconditioned after every operation, additional equipment is required for the same.
9. Arced SF_6 gas is poisonous and should not be inhaled.

8.7.7 Applications

A typical SF_6 circuit breaker consists of interrupter units. Each unit is capable of interrupting currents upto 60 kA and voltages in the range 50-80 kV. A number of units are connected in series according to system voltage. SF_6 breakers are developed for voltage ranges from 115 to 500 kV and power of 10 MVA to 20 MVA ratings and with interrupting time of 3 cycles and less.

Review Questions

1. *With neat figure, explain the construction and working of SF_6 circuit breaker. What are advantages applications and disadvantages of SF_6 breaker ?*

   AU : May-06,07,12,14, Marks 16, Dec.-05,07,12,14,15, Marks 13

2. *Discuss the properties of SF_6 that makes it suitable for application in circuit breakers.*

   AU : Dec.-05, Marks 6

3. *Give the reasons of using SF_6 circuit breaker.* **AU : May-15, Marks 8**

4. *Explain the construction, operating principles of SF_6 Circuit breaker with neat diagram.*

   AU : Dec.-22, Marks 13

8.8 Miniature Circuit Breaker (MCB)

A miniature circuit breaker is an electromechanical device which makes and breaks the circuit in normal operation and disconnects the circuit under the abnormal condition when current exceeds a preset value.

MCB is a high fault capacity current limiting, trip free, automatic switching device with thermal and magnetic operation to provide protection against overload and short circuit.

It is necessary to use MCB because of its following features,

1. Its operation is very fast and opens in less than one millisecond.
2. No tripping circuit is necessary and the operation is automatic.
3. Provides protection against overload and short circuit without noise, smoke or flame.
4. It can be reset very quickly after correcting the fault, just by switching a button. No rewiring is required.
5. It can not be reclosed if fault persists.
6. The mechanical life is upto or more than one lakh operating cycle.

Hence now a days MCBs are used rather than rewirable fuse.

Generally MCBs are rated for a.c. voltage of 240 V for single phase, 415 V for three phase or 220 V d.c. The current rating available is from 0.5 A to 63 A. It is available as

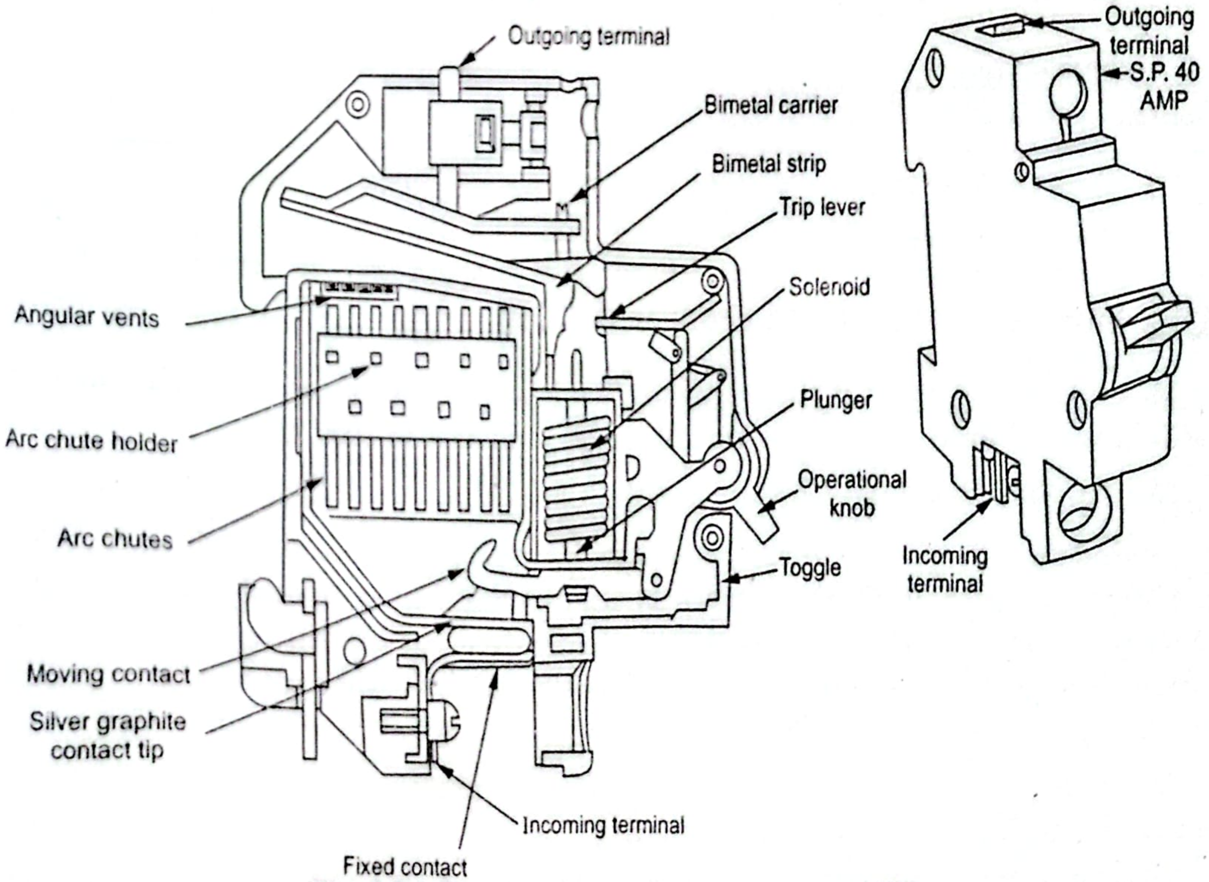

Outgoing terminal
Bimetal carrier
Bimetal strip
Trip lever
Solenoid
Plunger
Operational knob
Toggle
Angular vents
Arc chute holder
Arc chutes
Moving contact
Silver graphite contact tip
Incoming terminal
Fixed contact
Outgoing terminal
S.P. 40 AMP
Incoming terminal

Fig. 8.8.1 Construction and appearance of MCB

Single Pole (SP), Double Pole (DP), Tripple Pole (TP) with short circuit breaking capacity from 1 kA to 10 kA with a rated frequency.

A typical cross-section view of MCB and its practical appearance is shown in the Fig. 8.8.1.

8.8.1 Comparison of MCB and Fuse

Sr. No.	Fuse	MCB
1.	The operation of fuse is highly dependent on selection of its proper rating. If fuse wire is not selected properly then it results in non operation of fuse even in case of short circuit.	MCB instantly disconnects the supply automatically in the event of short circuit or overload. It thus eliminates the risk of fire and prevents damage to wiring system.
2.	If the fuse wire after operation is replaced with a newer one but go loose then it may be dangerous. Also to replace a blown fuse in between current carrying points is dangerous specially in dark.	Restarting power supply after tripping due to overload or short is easy.
3.	During replacement of fuse wire, the exact size of fuse wire may not be available. Also for replacement a kit of hand tools has to be kept ready	No maintenance and repairs is required for MCB. The distribution system employing MCB provides satisfactory operation and lasts for years.
4.	The board employing fuse is not compact	The board employing MCBs give beautiful look as it is compact and elegent.

Review Questions

1. *Write a note on MCB.*
2. *Compare MCB and Fuse.*

8.9 Moulded Case Circuit Breaker (MCCB)

MCCB is similar to MCB but used when the load currents exceed the capabilities of MCB. It is used for circuits having current ranges from 63 A to 3000 A.

The Fig. 8.9.1. shows the construction of MCCB.

Its working is based on thermal mechanism. It has a bimetallic contact which expands and contracts when there are changes in temperature. Under normal condition, the contacts are closed allowing current to pass. Under over load or short circuit condition, current exceeds its safe value. Due to this, heat is generated and the contacts are opened to interrupt the circuit.

Due to the interruption of high current, there is arc formation. Hence in MCCB there are arc extinguishers which suppress the arc.

There is a disconnection switch, with the help of which, the MCCB can be operated manually.

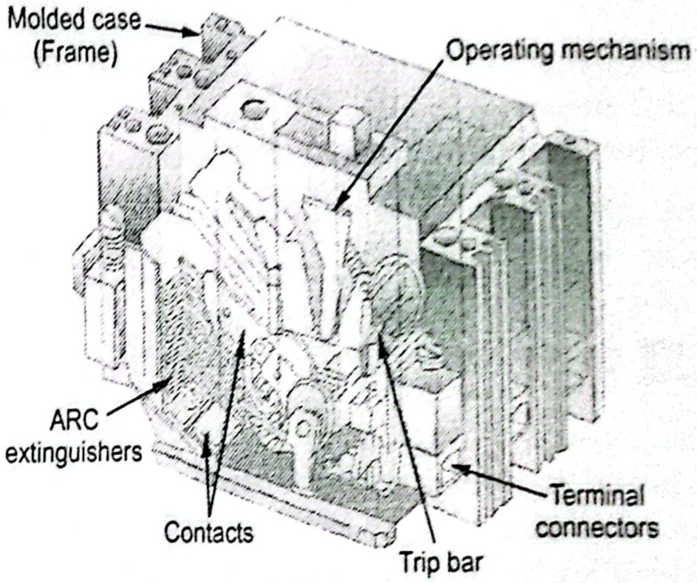


Fig. 8.9.1 MCCB

Practically it has adjustable trip settings and hence it can be used for high current applications.

It can be easily reset after the fault rectification. Thus it provides operational safely and convenience.

All the operating parts of MCCB are covered within a plastic moulded housing made in two halves. The two halves are joined together to form the whole structure.

The basic difference between MCB and MCCB is the current rating. Hence MCCBs are used for industrial and commercial applications such as main feeder protection, generator and motor protection, capacitor bank protection, welding applications and applications which require adjustable trip setting.

Review Question

1. *Write a note on MCCB.*

8.10 Vacuum Circuit Breakers

AU : May-04,05,06,11,15,17,18, Dec.-10,16

In vacuum type of circuit breakers, vacuum is used as the arc quenching medium. It is superior medium than any other arc quenching medium as vacuum offers highest insulting strength.

If we consider that the contacts of circuit breakers are opened in vacuum, the interruption occurs at first current zero. The dielectric strength of the contact space builds up very rapidly at a rate which is very much higher than that with other circuit breakers.

When the contacts of the breaker are opened in vacuum, an arc is produced between the contacts due to ionisation of metal vapours of contacts, which can be explained by field emission theory. An intensely hot spot is created at the instant of contact separation because of high current density. But the arc is quickly extinguished as metallic vapours, electrons and ions produced during the arc are condensed on the surface of the breaker. This will lead to fast recovery of dielectric strength. This is an important feature of vacuum as an arc quenching medium which will assist arc extinction and restriking of arc is prevented. The vacuum circuit breaker consists of one or more vacuum interrupter units per pole.

The vacuum switching devices have several merits such as high rate of rise of dielectric strength, silent operation, suitability for repeated operations, simple operating mechanism, free from explosion and long life.

The unique quality of vacuum interrupters is that the contacts are required to be travelled by small distance and less weight of moving contacts. Many repeated operations can be performed with this type of breaker.

8.10.1 Electrical Breakdown in High Vacuum

The pressure below about 10^{-5} mm of mercury are considered to be high vacuum. The charged particles from one electrode moving towards other at such a pressure will not cause collision with the molecules of residual gas. Hence ionization by collision of particles is less in vacuum as compared to in the gas.

If a small gap (say 0.5 mm) is kept between the electrodes in the vacuum and voltage is gradually increased, at a certain voltage the gap breaks down and current increases rapidly. The phenomenon is called **vacuum breakdown**. With pressure remaining constant the breakdown characteristics are influenced by surface, condition and material of electrodes.

Due to high arc energy, electrons emission takes place from surface of the electrodes. High heat is produced and core will be at very high temperature. Few spots having high current densities are produced. Thus thermal emission takes place from surface of electrodes which is a cause for arc formation in case of these breakers.

8.10.2 Construction

The Fig. 8.10.1 shows the schematic representation showing the constructional details of vacuum circuit breaker.

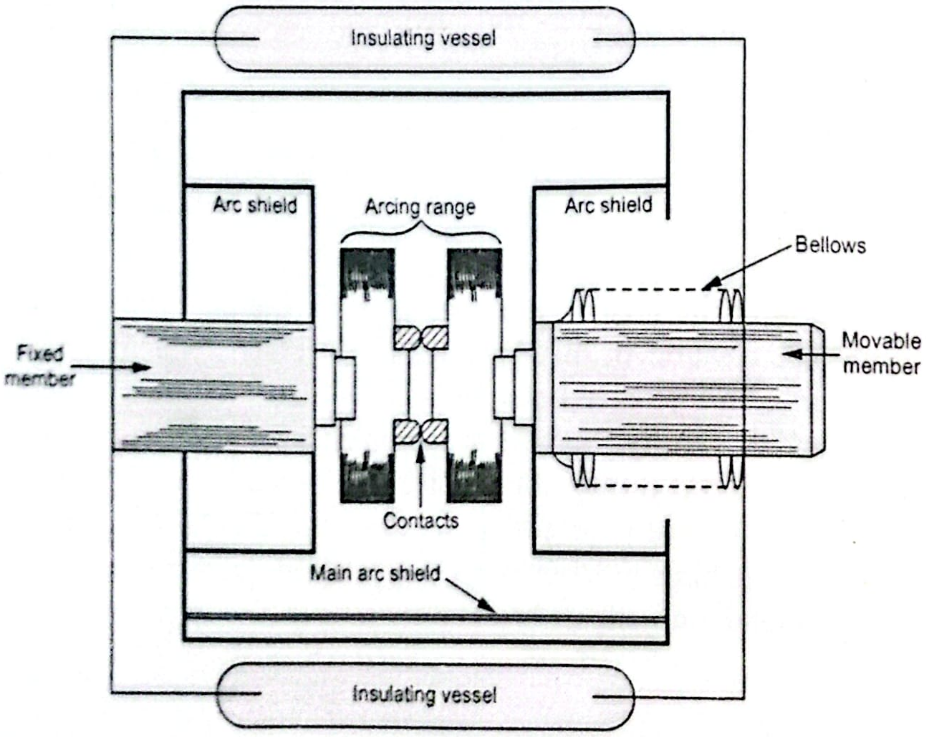


Fig. 8.10.1 Construction of vacuum circuit breaker

It consists of vacuum chamber in which fixed contact, moving contact and arc shield are mounted. The movable member is connected to the control mechanism by stainless steel bellows. The bellows permit the sealed construction of the interrupter. They are covered by protective shield. The contacts are made of large stem with large disc shaped faces. The disc is provided with symmetrical grooves such that segments of two contacts are not along same line. This geometry facilitates the rapid movement of arc instead of ramaining stable at one point and arc remains in diffused state. The enclosure is made up of impermeable insulating material like glass. The material should not be porous and should have capability to retain high vacuum. The supporting end flanges are made up of non-magnetic metal.

The arc shields or vapour shields are supported on insulating housing such that they cover the contact region. The metal vapour released from the contact surface during arcing is condensed on these shields and is prevented from condensing on the insulating enclosure.

The possibility of leak is eliminated due to permanent sealing of vacuum chamber. The outer insulator is made up of glass or ceramics.

8.10.3 Working

When the contacts are separated due to some abnormal conditions, an arc is struck between the contacts. The arc is produced due to ionisation of metal ions and depends very much on material of contacts.

The arc interruption process in vacuum interrupters is different from other types of circuit breakers. The separation of contacts causes release of vapour which is filled in the contact space. It contains positive ions liberated from contact material. The vapour density depends on the current in the arc. When current decreases, the rate of vapour release decreases and after current zero, the medium regains its dielectric strength if vapour density is reduced.

When current to be interrupted is very small (of the order of few hundred amps) in vacuum, the arc has several parallel paths. The total current is divided into many parallel arcs which repel each other and spreads over contact surface. This is called diffused arc which can be interrupted easily.

At high values of currents, the arc gets concentrated on a small region. It causes rapid vapourisation of the contact surface. The interruption of arc is possible if arc remains in diffused state. If it is quickly removed from the contact surface, the arc will be restriked.

Arc extinction in vacuum breakers is greatly influenced by material and shape of contacts and technique of condensing metal vapour. The path of the arc is kept moving so that temperature at any one point will not be high.

After final arc interruption there is rapid building up of dielectric strength which is pecularity of vacuum breaker. They are suitable for capacitor switching as it will give restrike free performance. The small currents are interrupted before natural current zero which may cause chopping whose level depends on material of contact.

The chopping levels are affected by,

a) The vapour pressure of cathode material with increase in vapour pressure, the chopping level is lowered.

b) The thermal conductivity, if thermal conductivity is low and the chopping level is also low. Current chopping level for some materials is given in the Table 8.10.1.

Material	Average value of chopped current in amperes
Tungsten	9.2
Silver	6
Tin	2
Copper	4
Aluminium	2.8

Table 8.10.1

8.10.4 Advantages

The advantages of vacuum circuit breaker are,

i) They are compact in size and have longer life.

ii) There are no fire hazards.

iii) There is no generation of gas during and after operation.

iv) There is no restriction on interruption of fault current. This is outstanding quality of vacuum circuit breaker.

v) They require less maintenance and quiet in operation.

vi) They can successfully withstand lightning surges.

vii) They have low arc energy.

viii) They have low inertia and hence smaller power is required for control mechamism.

8.10.5 Disadvantages

A major problem that occurs with this type of circuit breakers is that there is erosion of material from electrodes and evolution of gases from the electrodes during arcing. Using refractory materials may result into severe current chopping because of low pressure.

The gases are liberated from the electrode material in the following ways,

i) Evolution of gas from metal evaporated by anode and the cathode spots which are formed when arcing takes place.

ii) From the surface exposed to radiations from the arc, the gases are released.

iii) The gases are also released from the inactive portion of the electrodes due to the heat conduction from the portion of the electrodes which are arcing.

Experiments are carried out on copper and oxygen free high conductivity copper. But it releases more amount of gas. In contrast to that single crystal of copper was grown from molten metal which releases small quantity of gas. But the process is very slow, costly and commercially not feasible. The another possible solution to this problem is to use zone-refined copper which is gas free.

The metals like aluminium, copper, silver, tin etc were tested for electrode erosion. At high currents the cathode spots formed shows a high vapour pressure that is supplied by vapourisation. The loss from cathode, causes gain in weight for anode due to the condensation of cathode vapour on the anode when it is cold.

Another important thing that must be considered is that the electrodes should not weld with each other and dielectric strength of the gap must be recovered very rapidly.

Thus the requirements to be satisfied by a vacuum circuit breakers are complicated. Hence no single metal is suitable for the electrodes. Thus the compromise is made and it shows that use of dicopper magnesium (Cu_2Mg), dicesium copper ($CuCe_2$), copper bismuth (CuBi) gives the satisfactory performance.

8.10.6 Recovery Strength Characteristics

The satisfactory working of vacuum circuit breaker is possible if the electrical strength after arcing is properly recovered. In this type of the breaker, the conducting medium of the arc is supplied by contact erosion and recovery of electric strength mostly depends on condensation of electrode vapour.

A reduction in number of vapour ions lead to improvement in recovery strength.

When pressure is reduced to such a value that the breakdown voltage is independent of pressure then under this case, the factors affecting breakdown voltage are the type of contacts, contact surface etc. Highly polished electrodes has good breakdown strength.

8.10.7 Applications

In countries like India, the installation of such breakers proves to be effective as it requires little maintenance. They are employed for outdoor installations ranging from 22 kV to 66 kV. With limited rating ranging from 60 to 100 MVA they are suitable in many applications.

Recently installed capacitor of such breakers are 11 kV, 25 kV and 33 kV.

Thus for voltages upto 36 kV, vacuum circuit breakers with single interrupter is becoming extremely popular for metal enclosed switchgear, arc furnace installations, auxiliary switchgear in generating stations and other industrial applications.

Review Questions

1. *Explain the construction, working, advantages, applications and the disadvantages of vacuum circuit breakers.* **AU : May-04, Marks 8, May-11, 15, 18, Marks 10**
2. *Explain the arc interruption taking place in vacuum.* **AU : May-05, Marks 8**
3. *What are the possible applications of vacuum circuit breakers ?*
4. *Explain the working of vacuum circuit breakers.* **AU : May-06, Marks 6**
5. *With a neat sketch, explain the working of vacuum circuit breaker.* **AU : Dec.-10,16, May-17, Marks 8**

8.11 Oil Circuit Breakers

AU : May-04,06,11

These are one of the oldest type of circuit breakers which employs oil as arc quenching medium. The contacts of the circuit breakers are separated in the oil. The bubbles of gas are formed which prevent restriking of the arc after the current reaches zero point of the cycle. There are two types of oil circuit breakers,

1) Circuit breakers using large quantity of oil or the bulk oil circuit breakers.

2) Circuit breakers using minimum quantity of oil called **minimum oil circuit breakers**.

After the current zero, the oil moves in the arc space which is an important part of the action of an oil circuit breaker which may be effected by,

1) The pressure developed due to natural head of oil above contacts.

2) The pressure generated by the action of arc current itself.

3) The pressure developed by external parameters.

Thus the oil circuit breakers are further grouped into following categories,

1) Plain break oil circuit breakers.

2) Self generated pressure oil circuit breakers (also called self blast oil circuit breakers.)

3) Externally generated pressure oil circuit breakers (also called force blast oil circuit breakers.)

8.11.1 Plain Break Oil Circuit Breaker

It consists of a strong, weather tight earthed tank containing oil upto certain level and air above the oil level. Both the fixed and moving contacts are immersed in oil.

When the contacts are separated, an arc is struck between the contacts with production of large amount of heat. This will increase the temperature to near about 5000 ° K which will vapourize the oil into gases such as hydrogen with small percentage of methane, ethylene and acetylene. With the withdrawl of moving contact, arc length increases and gas formation rate decreases as temperature lowers.

When distance between fixed contact and moving contact reaches at critical value, the arc gets extinguished at some current zero.

There are two types of plain-break oil circuit breakers,

a) Single break oil circuit breaker. b) Double break oil circuit breaker.

8.11.1.1 Single Break Oil Circuit Breaker

The single break oil circuit breaker principle is represented in the Fig. 8.11.1. The in and out of the current is through the terminal bushings. There is only one arc which is struck between the fixed and moving contact. The current breaks at one bushing and the moving contact is supported by the other bushing through sliding contact.

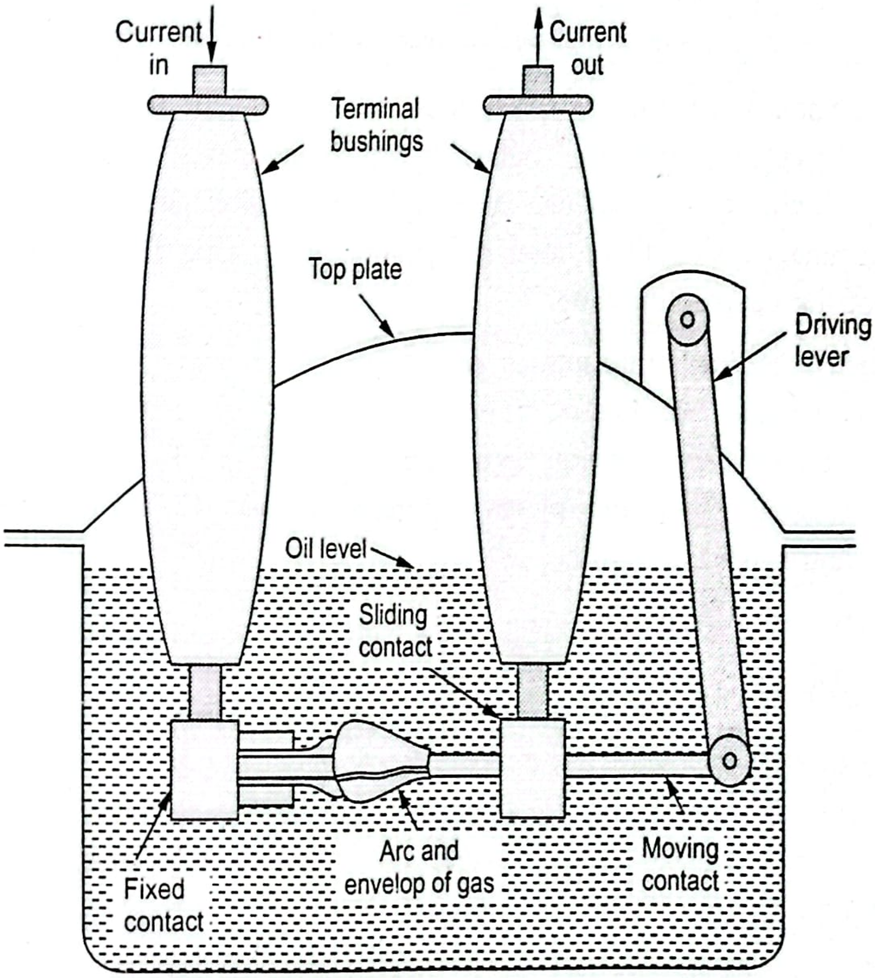

Current in
Current out
Terminal bushings
Top plate
Driving lever
Oil level
Sliding contact
Arc and envelop of gas
Moving contact
Fixed contact

Fig. 8.11.1 Single break oil circuit breaker

8.11.1.2 Double Break Oil Circuit Breaker

The principle of this type of circuit breaker is shown in the Fig. 8.11.2. There are two fixed contacts associated with terminal bushing which makes contacts with the moving contacts during normal operating condition. The lever containing the moving contacts can be operated with the help of crank.

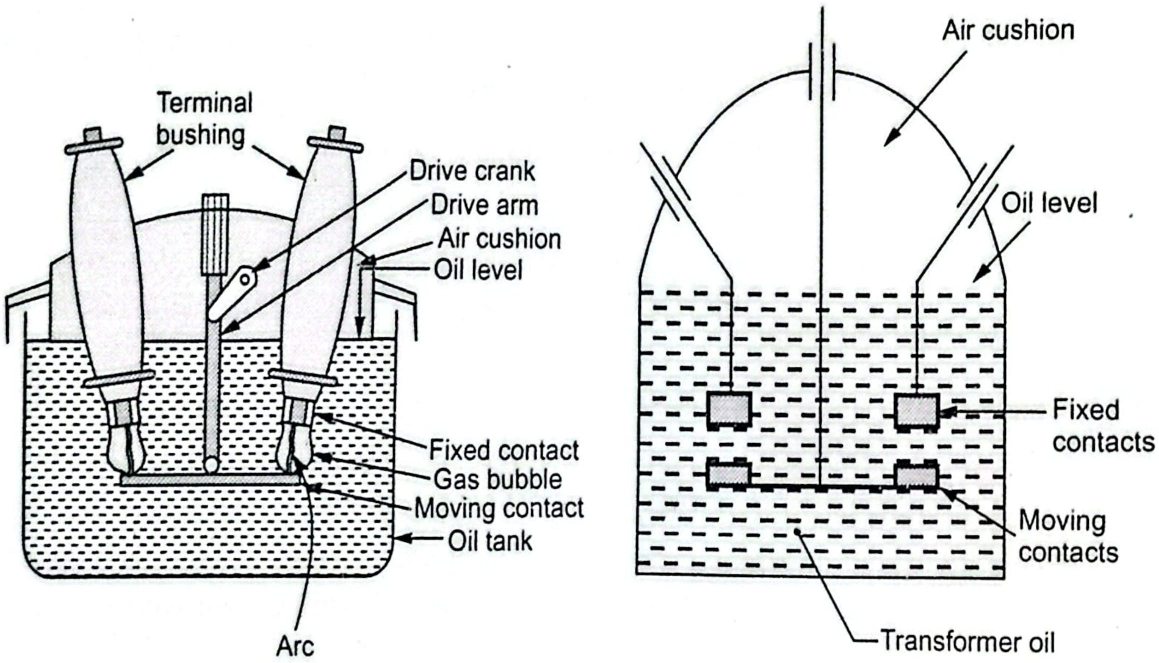

Terminal bushing
Drive crank
Drive arm
Air cushion
Oil level
Fixed contact
Gas bubble
Moving contact
Oil tank
Arc
Air cushion
Oil level
Fixed contacts
Moving contacts
Transformer oil

Fig. 8.11.2 Double break circuit breaker

When the contacts are separated, two arcs are drawn. Thus there are two breaks in series. This can achieve rapid arc lengthening which eliminates the need for a specially fast moving contact speed. But this introduces unequal voltage distribution across the breaks with uneven sharing of total interrupting duty. One break may take 70 to 80 percent of the interrupting duty.

When such a breaker interrupts an earth fault, the recovery voltage is not equally divided between the two breaks. This statement can be very well understood by considering the equivalent electrical circuit shown in the Fig. 8.11.3, where C_1 represents capacitance between fixed and moving contacts whereas C_2 represents capacitance between moving contact and earth.

Let I be the fault current

From the Fig. 8.11.3 (b),

$$V_1 = \frac{I}{\omega C_1} \text{ volts}$$

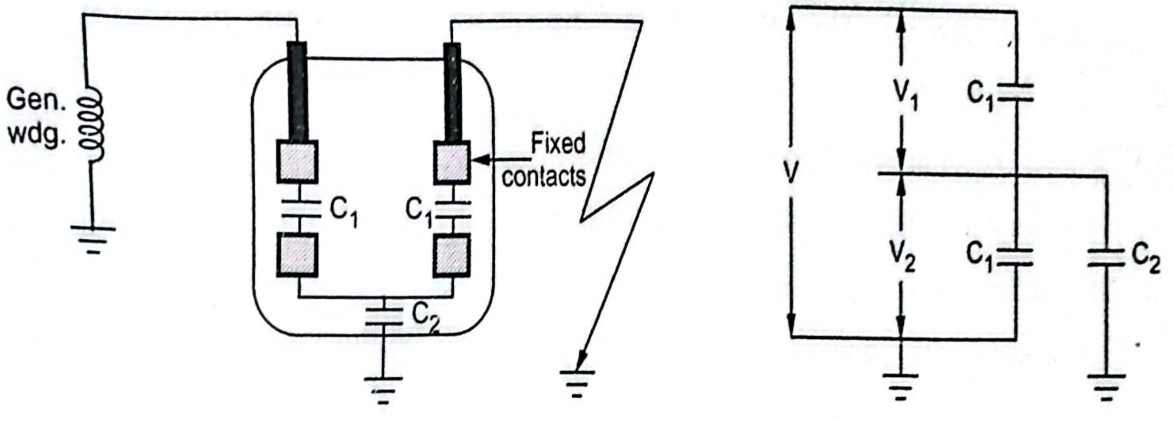
$$V_2 = \frac{I}{\omega (C_1+C_2)} \text{ volts}$$

Let $C_1 = 10$ pF and $C_2 = 40$ pF being typical values in practice.

$$\text{Now,} \quad \frac{V_1}{V_2} = \frac{\omega (C_1+C_2)}{\omega C_1} = \frac{C_1+C_2}{C_1}$$

$$\therefore \quad \frac{V_1}{V_2} = \frac{10+40}{10} = \frac{50}{10} = 5$$

$$\therefore \quad V_1 = 5\,V_2$$



(a) (b) Equivalent circuit

Fig. 8.11.3

It can be seen from the above expression that about 83 % of the system voltage appears across gap and only 17 % appears across gap. In order to equalize the voltage across the gaps, high resistances or capacitors are connected across them.

Let a capacitor of 50 pF be connected as shown in the Fig. 8.11.4.

$$\text{Now,} \quad \frac{V_1}{V_2} = \frac{C_1+C_2+C_3}{C_1+C_3} = \frac{10+40+50}{10+50} = \frac{100}{60} = 1.66$$

$$\therefore \quad V_1 = 1.66\, V_2$$

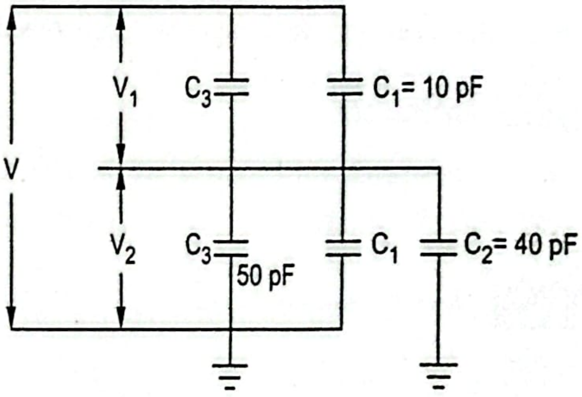


Fig. 8.11.4 Capacitive voltage grading

Thus V_1 becomes equal to 1.66 times that of V_2. If value of C_3 is chosen to be high then the difference between V_1 and V_2 can be further reduced. If instead of capacitors high values of resistors are used it will also cause damping. The resistance values are generally of the order of 10,000 to 100,000 ohms. The resistor selected may be non-linear one.

8.9.1.3 Factors affecting Performance of Plane Break Oil Circuit Breaker

The factors which influence the performance of plain break oil circuit breakers are as follows,

i) The critical length of the break.

ii) The speed of the contact movement. In order to extinguish the arc earlier, the speed should be high therefore double break circuit breakers are preferred.

iii) The head of oil above the contacts.

iv) The clearance between the live contacts and the earthed pressurized tank.

The factors which influence on increased breaking capacity are considerable head of oil and large clearances. Thus for large breaking capacity, the circuit breaker will be large.

8.11.1.4 Advantages of Plain Break Oil Circuit Breaker

The various advantages of plain oil circuit breaker are,

i) The arc energy is easily absorbed by the oil due to its decomposition.

ii) The gases formed due to oil decomposition has good cooling properties.

iii) The cooling surfaces formed by surrounding oil is close to the arc.

iv) After current zero a flow of cool oil flows in the contact space which is having dielectric strength.

v) The oil used acts as an insulator.

8.11.1.5 Disadvantages of Plain Break Oil Circuit Breaker

The various disadvantages of plain break oil circuit breaker are,

i) There is no special control over the arc other than the increase in length by separating the moving contacts. Hence large arc length is required for faithful interruption.

ii) These breakers have long and inconsistent arcing times.

iii) These breakers do not permit high speed interruption.

8.11.1.6 Applications

Such types of circuit breakers are suitable upto 150 MVA capacity and hence installed in low capacity applications having voltages not more than 11 kV.

8.11.2 Self Generated Pressure Oil Circuit Breaker

This type of circuit breakers are also called self blast oil circuit breakers where arc control is provided by internal means. The pressure developed by the arc is used in speeding up the movement of oil in the contact space at the instant after the current zero. This is achieved by surrounding the contact by a pressure chamber. This will make it possible to increase the breaking capacity of such circuit breaker while the arcing time is reduced.

The action of arc will itself set up pressure which is dependent on magnitude of currents. Thus proper design of pressure chamber must be done in order to ensure that pressure developed is sufficient to extinguish the arc at low currents, while it should not be excessive which may break the chamber at heavy currents. Thus a wide variety of designs are possible. Some of them are discussed below.

8.11.2.1 Plain Explosion Pot

This is shown in the Fig. 8.11.5. It consists of a rigid cylinder made up of a insulating material. The cylinder contains the fixed and moving contacts. The moving contact is a cylindrical rod which can pass through a small opening called throat. The motion of moving contact is vertical.

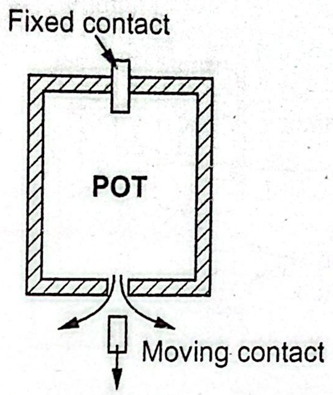


Fig. 8.11.5 Plain explosion pot

Whenever fault occurs in the system the contacts will start separating with the formation of arc in between them. The heat contained in the arc causes the decomposition of the oil into a gas at very high pressure in the pot. This high pressure forces the oil and gas around the arc to extinguish it.

It can be seen that if the final arc interruption does not take place while the moving contact is inside the pressure chamber then it occurs immediately after the moving contact leaves the pot as emergence of moving contact from the pot allows a high velocity axial blast of gas to release through the throat producing rapid arc extinction. As the arc extinction takes place axially of the arc, it is also called axial explosion type.

The major drawback with this type is that it cannot be used for very high or very low fault currents. At low fault current values, the pressure developed is small thus arcing time is increased. On the other hand at high fault currents due to very high pressure developed there is possibility of bursting the explosion pot or chamber. Therefore it is suitable for moderate short circuit currents only.

8.11.2.2 Cross Jet Explosion Pot

It is the modification of plain explosion pot which is shown in the Fig. 8.11.5. The Fig. 8.11.6 shows the four stages of operation. It consists of cylinder made up of insulating material. There are channels on one side which act as arc splitters. The use of arc splitters is to increase the arc length which will assist arc extinction by lengthening the arc.

In stage 1 shown in Fig. 8.11.6 the moving contact has separated from the fixed contact and an arc is formed while in stage 4 final arc extinction is shown where the moving contact is out of the throat.

When a fault occurs, the moving contacts begin to separate. An arc is struck initially at the top of pot. The gas formed exerts pressure on the oil when the moving contact moves away from the arc splitter ducts, fresh oil is forced across the path of arc. The arc is then passed through the arc splitters due to which its length increases which causes the arc extinction.

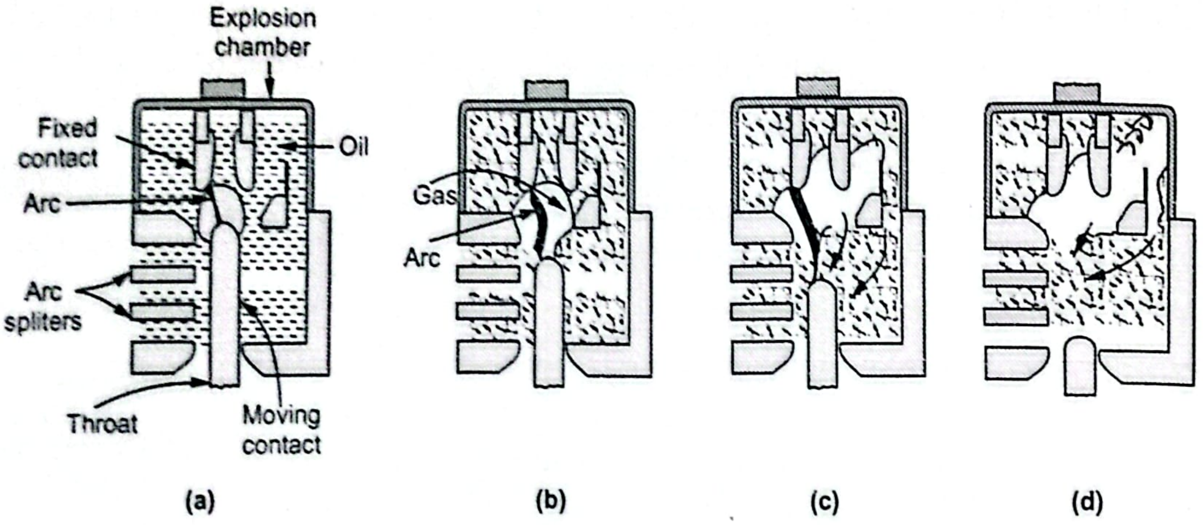


Fig. 8.11.6 Cross jet explosion pot

This type of circuit breaker gives satisfactory performance at heavy fault currents. However for small fault current, pressure developed by gas which is function of fault current is less and the performance is not satisfactory.

8.11.2.3 Self Compensated Explosion Pot

This type is essentially a combination of plain explosion and cross jet explosion type. Hence it can interrupt low as well as heavy short circuit currents effectively. It is represented in the Fig. 8.11.7.

It consists of two chambers, the upper chamber is the cross jet explosion pot with arc splitter ducts, while the lower chamber is the plain explosion pot.

When fault current is heavy, the rate of generation of gas is very high and it will act similar to cross jet explosion pot. When the moving contact moves away from the arc splitter duct, the arc extinction takes place.

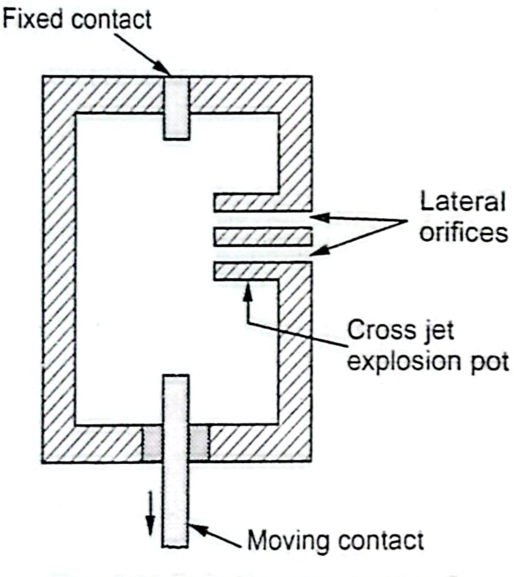


Fig. 8.11.7 Self compensated explosion pot

When fault current is low the rate of gas generation is low and the tip of moving contact takes some time to reach lower chamber. By this time the gas builds up sufficient pressure as there is no much leakage. When the moving contact comes out of throat the arc is extinguished by plain pot action.

With increase in fault current level, the operation will tend more and more similar to cross jet explosion pot. Thus interruption of fault current is possible in the wide range.

8.11.2.4 Oil Blast Explosion Pot

It is shown schematically in the Fig. 8.11.8. It consists of an intermediate contact along with moving contact. Initially the intermediate contact and lower moving contact move downwards together. An arc is struck between 1 and 2. The arc causes oil in upper chamber to be subjected to high pressure. When the intermediate contact has reached its maximum travel, the lower contacts start moving away from it and arc is struck between 2 and 3. Since the lower contact is hollow rod it is shut down by pressure which was developed by first arc. But this type has a disadvantage of long arcing time.

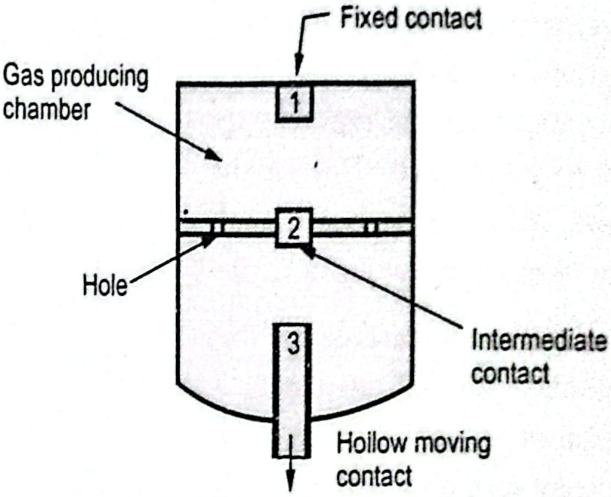


Fig. 8.11.8 Oil blast explosion pot

8.11.3 Forced Blast Oil Circuit Breakers

In the self blast oil circuit breakers, the pressure was developed due to the arc to force the oil across the arc path. The major disadvantage with this type is long arcing times and inconsistancy at lower currents as pressure developed is insufficient to force the oil in arc path. This difficulty is overcome in force blast oil circuit breakers which will not relay on the arc to generate the pressure but it is supplied from some external source.

This can be achieved by piston cylinder arrangement. The movement of piston is coupled mechanically to moving contacts or spring released by tripping mechanism. This arrangement enables high speed interruption.

When a fault occurs, the contacts get separated and an arc is struck. The piston forces a jet of oil towards the contact gap which will extinguish the arc. The typical scheme is shown in the Fig. 8.11.9.

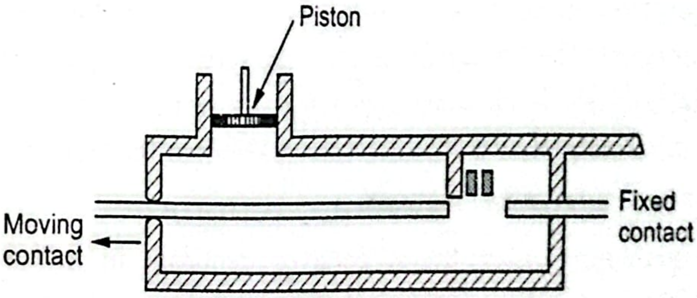


Fig. 8.11.9 Externally generated pressure breaker

The performance of the breaker is constant even at low currents as pressure developed is independent of fault current to be interrupted. This can be seen from following graph represented in the Fig. 8.11.10.

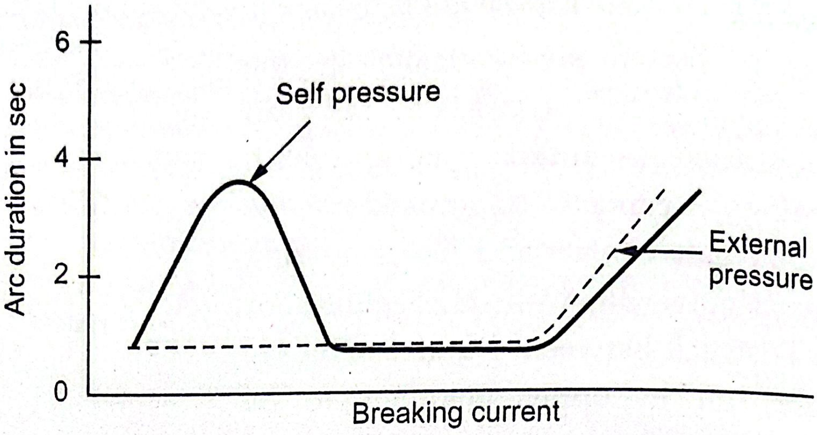


Fig. 8.11.10 Operating time-breaking current characteristics

Another advantage is that quantity of oil required is reduced considerably. If current chopping is there while interrupting small inductive currents then damping by resistance switching is required.

Review Questions

1. *Explain the operation bulk oil circuit breaker with suitable diagram.* **AU : May-11, Marks 6**
2. *State the causes of transient over voltage surges in a power system.* **AU : May-04, Marks 8**
3. *What is indirect lightning stroke ?* **AU : May-06, Marks 2**
4. *What are the advantages and disadvantages of bulk oil circuit breaker ?*

8.12 Low Oil or Minimum Oil Circuit Breaker

AU : Dec.-06,08,10,11,15,22, May-06,13

With the increase in system voltage the quantity of oil in bulk oil circuit breakers also increases. It gives additional expenses, increases the risk of fire and causes maintenance problem. This will make necessary the design of a type of circuit breakers which requires a low volume of oil. It is observed that oil serves two purposes. Firstly it acts as arc quenching medium and secondly it insulates live parts from earth. It is found that only a small percentage (about 10 %) of oil is used for arc extinction process and major part is used for insulation purposes.

A low or minimum oil circuit breaker uses a small container having oil which is just enough for arc extinction. The container of oil is supported on porcelain insulators, so that required insulation can be obtained for live parts from earth. Thus low oil circuit breaker has added advantage that it requires less space than the bulk oil type. This is an important consideration in large installations.

With respect to quenching of arc, the oil behaves identically in bulk as well as low oil circuit breaker. By using suitable arc control devices the arc extinction can be further facilitated in low oil circuit breaker.

8.12.1 Construction

The Fig. 8.12.1 shows the constructional details of a single phase minimum oil circuit breaker.

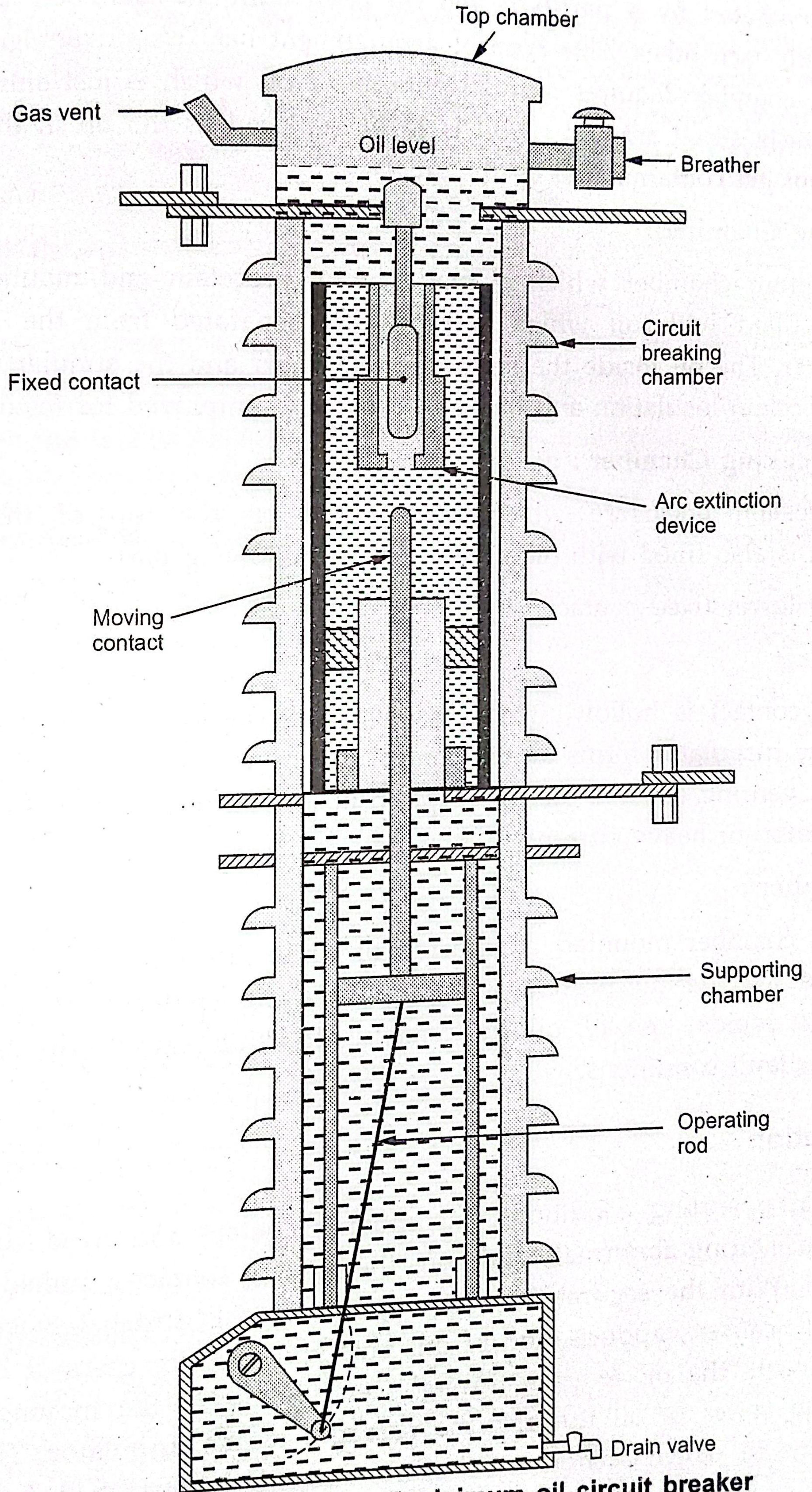

Top chamber
Gas vent
Oil level
Breather
Circuit breaking chamber
Fixed contact
Arc extinction device
Moving contact
Supporting chamber
Operating rod
Drain valve

Fig. 8.12.1 Construction of minimum oil circuit breaker

It consists of two separate compartments which are separated from each other. Both these compartments are filled with the oil. The upper chamber is called the **circuit breaking chamber** while the lower chamber is called the **supporting chamber**. The two chambers are separated by a partition and oil from both the chambers are prevented from mixing with each other. This type of arrangement has two advantages. Firstly the circuit breaking chamber requires a small volume of oil which is just sufficient for arc extinction. Secondly small amount of oil is to be replaced as the oil in the supporting chamber does not get contaminated by the arc.

1) Supporting Chamber :

This is a bottom chamber which is made up of procelain and mounted on metal chamber. It is filled with oil which is physically separated from the oil in circuit breaking chamber. The oil inside the supporting chamber and the annular space formed between the porcelain insulation and backelised paper is employed for insulation.

2) Circuit Breaking Chamber :

It is a porcelain enclosure which is mounted on the top of the supporting compartment. It is also filled with oil and consists of following parts

i) Upper and lower fixed contacts ii) Moving contact

iii) Turbulator.

The moving contact is hollow. It consists of a cylinder which moves down over a fixed piston. The turbulator forms an arc control device and it has both axial and radial vents. The axial venting ensures the interruption of low currents whereas radial venting ensures interruption of heavy currents.

3) Top Chamber :

It is a metal chamber mounted on the top of circuit breaking chamber. It provides expansion space for the oil present in circuit breaking chamber. It also contains a separator which avoids loss of oil by centrifugal action caused by circuit breaker operation during fault conditions.

8.12.2 Operation

Under normal operating conditions, the moving contact and fixed contacts are in engaged position. During abnormal conditions the moving contact is pulled down by the tripping springs. With the separation of contacts, an arc is struck between them. The energy in the arc causes vapourisation of oil. This will produce gases at high pressure. This action prevents the oil to pass through central hole in the moving contact and results in forcing series of oil through the passages of the turbulator. The process of turbulation is one in which sections of the arc successively quenched, by the effect of separate streams of oil moving across each section.

8.12.3 Maintenance of Oil Circuit Breakers

The maintenance of oil circuit breakers consists of checking of contacts and dielectric strength of the oil. After fault has been interrupted by circuit breaker, fault current flows for short time or load currents for several times, its contacts may be burnt due to arcing. Also there may be some loss of dielectric strength of oil due to carbonisation. This will reduce rupturing capacity of the breaker. Thus periodic checking of circuit breakers is essential after regular interval of 3 or 6 months. Following points should be kept in mind while checking,

i) Check the current carrying parts. It they are burnt replace them.

ii) Check the dielectric strength of oil. If its colour is changed then it should be changed or reconditioned. The oil in good condition withstands 30 kV for one minute with 4 mm gap between electrodes.

iii) Check the insulation for any damage. Clean the surface with removal of carbon deposites with strong and dry fabric.

iv) The oil level should be checked.

v) The closing and tripping mechanism should be checked.

8.12.4 Advantages

The advantages of minimum oil circuit breaker are,

i) The quantity of oil required is small.

ii) The space requirement is reduced.

iii) The risk of fire is reduced.

8.12.5 Disadvantages

The disadvantages of minimum oil circuit breaker are,

i) Due to smaller quantity of oil, the degree of carbonisation is increased.

ii) The gases are difficult to remove from the contact space in time.

iii) The dielectric strength of the oil deteriorates rapidly as degree of carbonisation is high.

8.12.6 Applications

Minimum oil circuit breakers are now available for all voltages and for the highest breaking capacity hence preferred in most of the protection schemes.

Review Questions

1. *With a neat figure, explain the construction and working of a minimum oil circuit breaker. What are its advantages, disadvantages and applications ?*
AU : Dec.-08,10,11,15, May-13, Marks 16
2. *Explain the working of minimum oil circuit breaker.* **AU : May-06, Marks 10**
3. *Show sectional view of working portion of a typical minimum oil circuit breaker.*
AU : Dec.-06, Marks 16

8.13 HVDC Circuit Breaker

AU : Dec.-06, 07

In a.c. circuit breakers, arc extinction is achieved at the natural current zero of the a.c. waveform used. But in d.c. circuit breakers, natural zero of voltage and current is not available as both are continuously available. Thus for extinction of an arc, artificial current zero is required to be introduced. Such an artificial current zero is possible by connecting LC circuit in parallel with the circuit breaker. The LC circuit is responsible to produce oscillatory arc currents having many artificial current zeros. At one of the artificial current zero arc gets extinguished.

The Fig. 8.13.1 shows the principle of HVDC circuit breaker. The HVDC circuit breaker is nothing but a vacuum circuit breaker. The LC circuit along with a switch is connected in parallel with this circuit breaker.

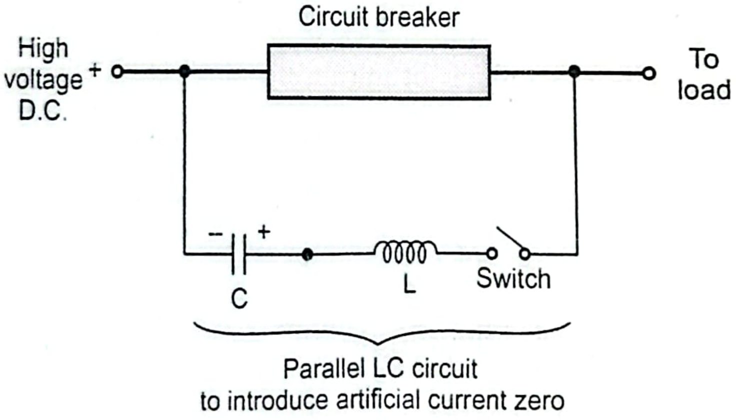


Fig. 8.13.1 HVDC circuit breaker

The capacitor C used is precharged capacitor with the polarities as shown in the Fig. 8.13.1. When the circuit breaker starts opening, the switch in the LC circuit gets closed. Due to the charged capacitor, the discharging current starts flowing in opposite direction to that of load current carried by the circuit breaker. Due to this, arcing current starts oscillating producing many natural zeros. Thus artificial commutation results and arc extinction is achieved.

The large transient recovery voltage is the main constraint in HVDC circuit breaker and circuit breaker must able to withstand it. For successful operation of such a circuit breaker, the switch in LC circuit must be a high speed switch with a very fast response. Such systems are complex and very costly as they require costly protection and control systems.

Review Question

1. *Draw the schematic of a HVDC circuit breaker and explain its functioning.*

AU : Dec.-06, 07, Marks 8

8.14 Selection of Circuit Breaker

AU : Dec.-08,12

The following parameters are required to be known for selecting proper rating circuit breaker at a given location on a power system :

i) The maximum fault current which is to be interrupted by the breaker.

ii) The maximum current to be carried momentarily.

As it is discussed previously the fault current consists of both a.c. and d.c. components and its correct calculation is very complex. A simplified method is recommended by IEEE committee is given below :

1. To determine firstly the required interrupting capacity of circuit breaker the highest value of initial r.m.s alternating current for any type and location of fault. It can be considered as three phase fault as it carries maximum fault current except in some cases. This current can be obtained by using sub-transient reactance for generators and transient reactance for synchronous motors while induction motors are to be neglected. Following multiplying factors can be applied to take into account the d.c. components of currents and decrements of both a.c. and d.c. components.

8 cycle or slow breaker	1.0
5 cycle breaker	1.1
3 cycle breaker	1.2
2 cycle breaker	1.4

Before applying multiplying factor, all the given factors are increased by 0.1 for the breakers on the generator bus where 3 phase short circuit kVA exceed 500,000.

2. To determine the required rated momentary current with time 1 sec or less of a breaker. The calculation of highest value of initial r.m.s. a.c. current can be done as given in the step (1) except using sub-transient reactances of all the machines including induction motors. Multiply the value of current obtained by 1.6.

$$\therefore \quad \text{Momentary rated r.m.s. current of a circuit breaker} = 1.5 \times \frac{V}{X''_d}$$

Example 8.14.1 *A generator connected through 5 cycle CB to a transformer is rated 8000 kVA with the reactances of $X''_d = 10\ \%$, $X'_d = 16\ \%$ and $X_d = 100\ \%$. It is operating at no load and rated voltage when 3 phase short circuit occurs between breaker and transformer. Find :*

i) Sustained short circuit in breaker ii) The initial symmetrical r.m.s. current in breaker

iii) Maximum possible d.c. component of short circuit in breaker

iv) The momentary current rating of the breaker

v) Current to be interrupted by breaker vi) The interrupting kVA.

Solution : Let the base be 8000 kVA.

$$\therefore \quad \text{Sustained short circuit kVA} = \frac{8000}{100} \times 100 = \mathbf{8000\ kVA} \text{ as } X_d = 100\ \%$$

$$\text{Sustained short circuit current} = \frac{\text{kVA}}{\sqrt{3} \times V_L}$$

$$\text{Let} \quad V_L = 13.8\ \text{kV}$$

$$\therefore \quad \text{Sustained short circuit current} = \frac{8000}{\sqrt{3} \times 13.8} = 334.70\ \text{A}$$

$$\text{Sub-transient short circuit kVA} = \frac{8000}{10} \times 100 = 80000$$

$$\text{Sub-transient or initial symmetrical current} = \frac{8000 \times 100}{10 \times \sqrt{3} \times 13.8} = \mathbf{3347.05\ A}$$

$$\text{Maximum possible d.c. component} = \sqrt{2} \times 3347.05 = \mathbf{4732.73\ A}$$

$$\text{Momentary current rating} = 1.6 \times 3347.05 = \mathbf{5355.28\ A}$$

$$\text{Current to be interrupted} = 1.1 \times 3347.05 = \mathbf{3681.75\ A}$$

$$\text{Interrupting kVA} = \sqrt{3} \times 3681.75 \times 13.8 = \mathbf{87999.836\ kVA}$$

Example 8.14.2 *A 11 kV generator connected through 5 cycle circuit breaker to transformer rated 8000 kVA with the reactance of and $X''_d = 9\ \%$, $X'_d = 5\ \%$, $X_d = 100\ \%$. It is operating at no load and rated voltage, when 3 phase short circuit occurs between breaker and transformer. Find*

i) Sustained short circuit current in breaker ii) Initial RMS current in circuit breaker

iii) Maximum possible DC component of short circuit current in circuit breaker

iv) Momentary current rating of the breaker v) Current to be interrupted

vi) Interrupting kVA.

Solution : Let the base kVA be 8000 kVA , V = 11 kV

$$\text{Sustained short circuit kVA} = \frac{8000}{100} \times 100 = 8000 \text{ as } x_d = 100\ \%$$

i) Sustained short circuit current in breaker $= \frac{\text{kVA}}{\sqrt{3} \times V_L} = \frac{8000 \times 10^3}{\sqrt{3} \times 11 \times 10^3} = \mathbf{419.89\ A}$

ii) Initial r.m.s. current in circuit breaker $= \frac{\text{kVA}}{\sqrt{3} \times V \times x_d''} = \frac{8000 \times 10^3}{\sqrt{3} \times 11 \times 10^3 \times 9 \times 10^{-2}}$

$= \mathbf{4665.45\ A}$

iii) Maximum possible d.c. component $= \sqrt{2} \times \text{Initial r.m.s. current} = \sqrt{2} \times 4665.45$

$= \mathbf{6598\ A}$

iv) Momentary current rating of breaker $= 1.6 \times \text{Initial r.m.s. current}$

$= 1.6 \times 4665.45 = \mathbf{7464.73\ A}$

v) Current to be interrupted for 5 cycle circuit breaker $= 1.1 \times \text{Initial r.m.s. current.}$

$= 1.1 \times 4665.45 = \mathbf{5131.9\ A}$

vi) Interrupting kVA $= \sqrt{3} \times V_L \times \text{Current to be interrupted}$

$= \sqrt{3} \times 11 \times 10^3 \times 5131.9 = \mathbf{97777.63\ kVA}$

Review Questions

1. *Discuss the selection of circuit breakers for different ranges of system voltages.*

AU : Dec.-12, Marks 8

2. *A generator connected through a 3-cycle circuit breaker to a transformer is rated 10 MVA, 13.8 kV with reactances of X_d'' = 10 %, X_d' = 15 % and X_d = 100 %. It is operating at no load and rated voltage when a 3-phase short circuit occurs between the breaker and the transformer. Determine*
   - *a) The sustained short circuit current in breaker;*
   - *b) The initial symmetrical rms current in the breaker;*
   - *c) The maximum possible d.c component of the short circuit current in the breaker;*
   - *d) The momentary current rating of the breaker;*
   - *e) The current to be interrupted by the breaker and*
   - *f) The interrupting kVA.*

AU : Dec.-08, Marks 8

[Ans. : 418.36 A, 4183.69 A, 5916.63 A, 6693.904 , 4602.05 A, 110 MVA]

8.15 Circuit Breaker Ratings

AU : May-06,12, Dec.-11,15

A circuit breaker is a mechanical switching device capable of making, carrying and breaking current under normal circuit conditions and also making, carrying for specified time and breaking current under specified abnormal conditions.

The circuit breaker is also required to perform some additional functions as the application demands such as,

i) To provide selectivity with breakers.

ii) To provide facility for remote closing and tripping.

iii) To provide facility for interlocking.

iv) To provide facility for indication.

Some of the important characteristics or ratings that must be possessed by every high voltage a.c. circuit breaker arc as follows,

1. Rated voltage.
2. Rated insulation level.
3. Rated normal current.
4. Rated frequency.
5. Rated duration of short circuit.
6. Rated short circuit breaking current.
7. Rated short circuit making current.
8. Rated peak withstand current.
9. Rated TRV for terminal fault.
10. Rated operating sequence.
11. Rated supply voltage for opening and closing devices and auxiliary circuits.
12. Rated pressure of compressed gas for interruption.

8.15.1 Rated Voltage

It is a voltage of a circuit breaker which refers to higher system voltage for which it is designed. It is expressed in kV and the value is r.m.s. value. In case of three phase circuits it is nothing but phase to phase voltage. A circuit breaker must be assigned two voltage ratings one corresponding to maximum nominal system voltage and other maximum design voltage which indicated the maximum operating voltage which should not be exceeded.

8.15.2 Rated Insulation Level

The different circuit breakers connected in power system are subjected to power frequency over voltages due to various effects such as regulation, Ferranti effect etc. The circuit breaker must withstand this overvoltage. This can be tested by carrying out different tests. During some single phase to ground faults voltage of healthy line to earth increases. So higher values of insulation are suggested. The insulation is provided for each pole external and internal between live parts and earth. It is also provided between poles and between terminals of same pole internal and external.

8.15.3 Rated Current

It is defined as r.m.s. value of the current that can be carried by the circuit breaker continuously with temperature rise within the specified limits. Some of the preferred values of rated currents are 400, 630, 800, 1250, 1600, 2000 A r.m.s. etc. The rated current of a circuit breaker can be checked by carrying out temperature rise tests. The current carrying parts along with the contacts are designed based on temperature rise. For given cross section of a conductor and certain value of current, the temperature rise is dependent on conductivity of material. Hence while designing high conductivity material must be used. If material is having low conductivity then cross-section of the conductor is increased.

8.15.4 Rated Frequency

The performance of circuit breaker is greatly influenced by frequency. The different characteristics like breaking capacity are based on rated frequency. With increase in frequency, eddy currents in the metallic parts will increase which will cause more heating and rise the temperature of current carrying parts. Hence if a circuit breaker designed for one particular frequency is used at some another frequency then temperature will not remain in specified limits. So the rating is to be changed accordingly.

The breaking time is also affected by the frequency as it is associated with time for half cycles during arc extinction. The breaking time decreases with increase in frequency.

The frequency has a pronounced effect on TRV and rate of rise if TRV. So a circuit breaker designed for one particular frequency cannot used for other frequency unless the results are faithful for that frequency.

8.15.5 Rated Duration of Short Circuit

The short time current of a circuit breaker is r.m.s. current that it can carry in a closed position during specified time under given conditions. It is expressed in kA for a period of one second. The rated duration of short circuit is commonly 1 second. The circuit breaker must carry the current equal to its breaking capacity for this duration. This can be tested by carrying out short time current test and checked that the poles are not getting damaged or welded. The insulation should not be damaged. The poles must be able to withstand the mechanical force developed. The design for normal current rating is sufficient to carry short circuit current for 1 sec.

8.15.6 Rated Short Circuit Breaking Current

It is r.m.s. value of highest short circuit current which the circuit breaker is capable of breaking under specified conditions of TRV and power frequency voltage and expressed in kA r.m.s. at contact separation.

The voltage appearing across circuit breaker after arc interruption is nothing but Transient Recovery voltage. The limit on breaking current is governed by specified conditions of TRV and power frequency recovery voltage. This limit is determined by carrying short circuit test. The current waveform is shown in the Fig. 8.15.1.

The breaking current is expressed by two values

i) The r.m.s. value of a.c. component at the instant of contact separation given by $\frac{I_{AC}}{\sqrt{2}}$.

ii) The percentage d.c. component at the instant of contact separation given by $\frac{I_{DC} \times 100}{I_{AC}}$.

The standard values of r.m.s. currents are 8, 10, 123, 16, 20, 25, 31, 5, 40 kA etc.

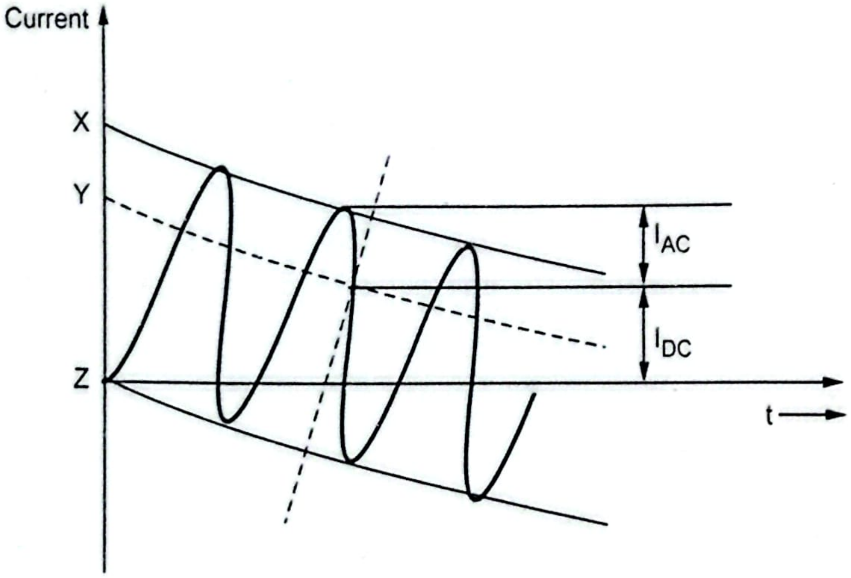


Fig. 8.15.1

In earlier days the breaking capacity is expressed in MVA so that fault levels can also be determined. But now it is expressed in kA for specified conditions of TRV.

8.15.7 Rated Short Circuit Making Current

This is defined as the peak value of first current loop of short circuit current which the circuit breaker is capable of making at its rated voltage. There are certain cases under which the circuit breaker may close when fault is existing. Under such cases current reaches to maximum value at peak of first current loop. The circuit breaker should be able to close without difficulty and withstand the mechanical forces developed during a closure. This is checked by carrying out making current test.

$$\text{Rated making current} = 1.8 \times \sqrt{2} \times \text{Rated short circuit breaking}$$

$$= 2.55 \times \text{Rated short circuit breaking current}$$

$\sqrt{2}$ in above expression converts r.m.s. value to peak value while factor 1.8 is considered for doubling effect of short circuit current.

8.15.8 Rated Peak Withstand Current

It is defined as the instantaneous value of short circuit current which circuit breaker can withstand safely in closed position. It is expressed in terms of kA instantaneous. The value suggested for this current is equal to rated short circuit making current. To test this peak withstand current short circuit with maximum asymmetry is applied to circuit breaker in one phase. The peak withstand current test is combined with short time current test. The stresses produced due to high current must be sustained by the circuit breaker.

8.15.9 Rated TRV for Terminal Faults

The TRV waveform can be specified by various methods such as specifying the peak value and time to reach it or specifying parameters which will decide the line segment which will represent TRV wave. The methods are respectively called two parameter and four parameter method. The two parameter method is represented in the Fig. 8.15.2.

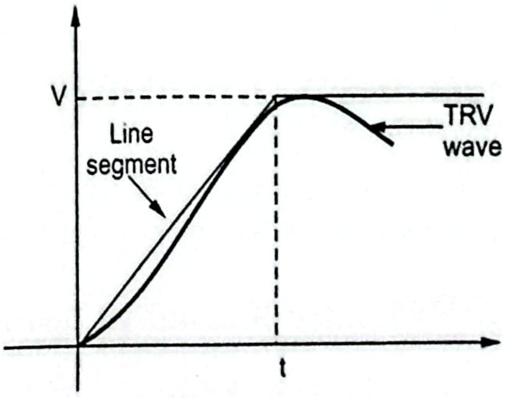


Fig. 8.15.2

The circuit breakers must be provided with rated TRV. The breaking current test is carried out on circuit breaker with specified TRV.

The standards provide different parameters such as voltage, and time to plot the line segments. The TRV wave can be drawn within the segment. The circuit breaker must be tested for S.C. breaking current test with TRV waveform above standard waveform.

8.15.10 Rated Operating Sequence

It represents the sequence of opening and closing operations which circuit breaker can perform under specified conditions. As per specifications the circuit breaker should be able to perform the operating sequence as per one of the ways

i) O – t – CO – T – CO ii) CO – t′ – CO

where O = Operation of opening
t = 3 minutes for circuit breaker not to be used for rapid auto-reclosure
CO = Closing followed by opening
T = 3 minutes
t′ = 15 sec for circuit breaker not to be used for rapid auto-reclosure

8.15.11 Rated Supply Voltage for Closing and Opening Devices

The performance of auxilary supply circuits and operating mechanisms is important in addition to ratings of or main circuit and poles. The supply voltage is provided by auxiliary circuits to the trip coil and closing coil which are having certain minimum voltage below which it will not operate. For correct operation the frequency must be properly chosen. The rated supply voltage and supply frequency of closing and opening devices and auxiliary circuits is important.

8.15.12 Rated Interrupting Duties

In case the circuit breaker is not used for auto reclosing then its short circuit interrupting duty is given by, B-3-MB-3-MB where B denotes breaking. MB denotes making followed by breaking without any intentional time delay while 3 indicates time interval in minutes.

The circuit breakers used for auto reclosing must be able to perform the following interrupting duty, B-D_t-MB where D_t is the dead time which is expressed in cycles.

8.15.13 Rated Pressure of Compressed Gas

The air blast circuit breaker and some of the SF_6 breakers use pneumatic while some other SF_6 breakers use hydraulic operating mechanisms where minimum and maximum values of pressures are specified certain tests like no load test are carried out with conditions of the pressures. The pressure switches are also fitted in the auxiliary systems of the operating mechanism.

Some additional rated characteristics are to be specified in certain cases like rated characteristics for short-line faults for circuit breakers controlling overhead lines rated 52 kV and above. Rated line charging current for circuit breakers controlling overhead lines rated 72.5 kV and above.

There are certain special switching duties like capacitor switching, reactor switching, DC switching, inductive current switching. The stress produced is usual and severe. Different circuit breakers behaves differently. The interruption of low inductive currents is achieved by SF_6 while capacitor current switching is done excellently by VCB. Depending upon the type of application the following characteristics are specified,

i) Rated out of phase breaking current.

ii) Rated cable charging breaking current.

iii) Rated single capacitor bank breaking current.

iv) Permissible switching overvoltages.

v) Rated capacitor bank in rush overvoltages.

vi) Rated small inductive breaking current.

vii) Rated time quantities.

viii) Repeated operating duty.

In actual design of circuit breakers following parameters are considered :

1. Current rating
2. Breaking capacity
3. Making capacity
4. Type of protective mechanism
5. Short time rating
6. Type of mechanism
7. Accessories
8. Indications
9. Locks and interlocks
10. Operational life
11. Ease of maintenance
12. Volume / weight
13. Control voltage
14. Availability of spares
15. Cost

Depending upon the above parameters the different circuit breakers are designed for their efficient operation.

Example 8.15.1 *An OCB is rated as 3 phase, 1500 Amp, 2000 MVA, 33 kV, 3 sec. Determine : i) The breaking current ii) Making current iii) Short time current iv) Rated normal current.*

Solution : I = 1500 A, 2000 MVA, V_L = 33 kV

i) The breaking current $= \frac{VA}{\sqrt{3}\,V_L} = \frac{2000\times10^6}{\sqrt{3}\times33\times10^3}$ = **34.99 kA**

ii) Making current = 2.55 × Breaking current = **89.226 kA**

iii) Short time current = **34.99 kA for 3 sec**

iv) Rated normal current = I = **1500 A**

Review Questions

1. *Describe various types of ratings of circuit breakers.* **AU : Dec.-11, 15, Marks 8**
2. *Explain the following with reference to circuit breakers*
   i) Breaking capacity ii) Making capacity iii) Show time capacity iv) Rated current.
   AU : May-06, Marks 10, May-12, Marks 8

8.16 Type Tests

As mentioned earlier these tests are carried out on first few circuit breakers to prove the rated characteristics of the breakers. The necessary information which includes assigned ratings, drawings, reference standards, rated operating pressure and voltage, support structure etc. must be supplied to the testing authorities before conducting these tests. These details are included in the type tests report. After certifying the breaker by carrying out these tests, there should not be any change in design.

Type tests are classified as follows,

a) Mechanical tests.

b) Tests of temperature rise, millivolt drop test.

c) High voltage test.

d) Basic short circuit test.

   i) Making test

   ii) Breaking test

   iii) Operating sequence tests at 10 %, 30 %, 60 %, 100 % of rated breaking current with specified TRV conditions.

e) Critical current tests.

f) Single phase short circuit test.

g) Short time current test.

In addition to above tests some more tests are recommended on circuit breakers to be used in specific applications, which are,

a) Short line fault tests.

b) Out of phase switching tests.

c) Cable charging current switching test.

d) Capacitive current switching tests.

e) Small inductive current breaking tests.

f) Reactor current switching tests.

Review Question

1. *What are the various types of type tests that are carried out on circuit breakers ?*

8.17 Routine Tests

Before dispatch of circuit breakers, these tests are performed. Routine test is defined as a test of every circuit breaker made to the same specifications. They include the following tests.

a) Mechanical operation tests.

b) Millivolt drop test, measurement of resistance.

c) Power frequency voltage tests.

d) Voltage tests on auxiliary circuits, control circuits.

The quality of the circuit breaker can be very well checked by these tests. Also any defects in the materials and construction is detected.

Review Question

1. *What are various types of routine tests ?*

8.18 Development Tests

These tests, are very much essential to observe the effect of different parameters on the circuit breakers performance. Variety of tests are performed on individual items as well as on complete assemblies.

If a circuit breaker is tested frequently with change in its contact speed, then we can see the effect of contact speed on breaking capacity. The different parameters and their effects are theoretically predicted. Full scale prototypes are manufactured after testing and measurement. The data available in the company is used by the designers for example for the design of contacts, the configuration can be derived from available designs of contact assemblies.

Each subassembly has certain functional requirement e.g. the contacts should give low resistance in closed position. Therefore to verify the capability of contact configurations, development tests are conducted, depending on functional requirements. The modifications are done on the basis of these test results.

There are certain tests which are carried out on circuit breakers for further research and development. But these are not certification tests. Some of these tests are as given below.

1. Substitution test
2. Capacitance test
3. Compensation test

Let us study these tests in brief.

8.18.1 Substitution Test

Substitution test is carried out on the circuit breaker wherein number of tests at closely graduated capacities are conducted. This is generally carried out on oil circuit breakers where the current being interrupted acts as the internal source of extinguishing energy. The current which is being interrupted decides the duration of an arc. For low interrupting currents, breaking time is more while it is less for large interrupting currents.

The circuit breaker to be tested has capacity more than the testing equipment. This test is carrier out in setps which are given below

1. First the breaker is tested at full voltage and upto the current which can be supplied by the testing equipment. Let this current be I_1 and test voltge be V_1. The characteristics obtained are represented by curve I.
2. Next the breaker is tested at reduced voltage and upto current, say I_2, which is permitted by test equipment at voltage, say V_2. The time for breaker operation is recorded and the corresponding time-current characteristic is plotted which is represented by curve II.
3. In the similar manner, characteristic curve III is obtained upto current I_3 at reduced voltage V_3. This can be continued and number of characteristic curves are obtained with $V_1 > V_2 > V_3 > \ldots > V_n$ while I_1 is the permitted current by testing equipment at voltage V_1 and so on.

The characteristic curves are as shown in the Fig. 8.18.1.

The characteristics I, II, III, ... are plotted after carrying out number of tests on the breaker and these curves are extended by approximation. This is shown by dotted lines.

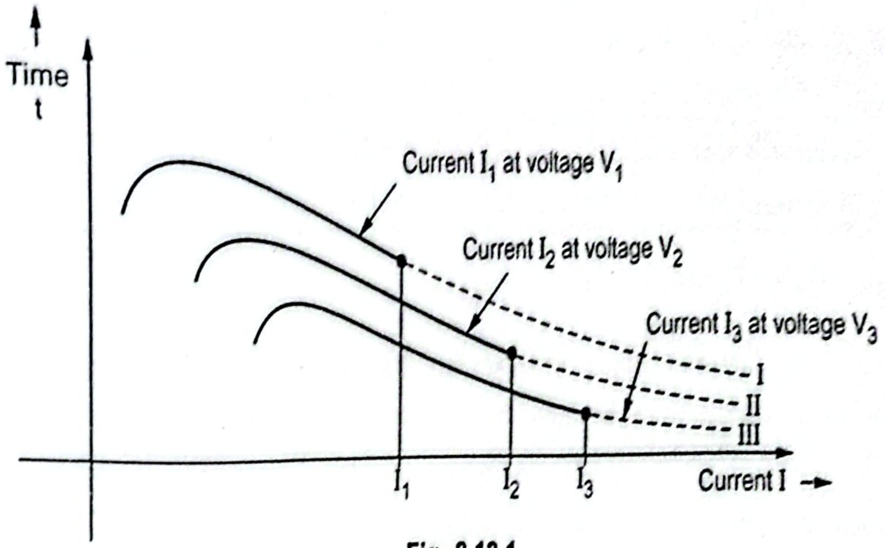


Fig. 8.18.1

This helps in predicting the breaker performance for those values of currents which are beyond the range of testing equipment.

8.18.2 Capacitance Test

In this test, the capacitor is connected in series with an inductor and a making switch. The capacitor is charged by a d.c. voltage source. The breaker contacts are connected across the circuit consisting of capacitor, inductor and making switch.

Capacitor C and inductor L forms L-C tank circuit which is oscillatory in nature. The circuit breaker which is under test is opened and the voltage across the capacitor is discharged through the open contacts of breaker in the form of an arc. This arc gets extinguished at current zero. This test helps in understanding the behaviour of the circuit breaker towards restriking voltage.

8.18.3 Compensation Test

In case of oil circuit breakers, current to be interrupted forms the internal source of extinguishing energy. For low interrupting currents, the breaker undergoes extremely difficult extinguishing conditions due to lack of building up of pressure between the contacts. The behaviour of breaker in such critical operating condition can be studied by conducting compensation test.

These tests are normally carried out in critical range of operating conditions. The data recorded during these tests involve, pressure in arc extinction device, lengths and durations of the arc. The tests are conducted at reduced voltage and this reduction in voltage is compensated by some other factor such as increased frequency, applying impulse voltage at current zero or increasing the current for reduced voltage as the pressure in the tank of oil circuit breaker is given by, $P = KV^{0.5} I^{1.2}$. Hence the test is called **compensation test**.

Review Questions

1. *What are development tests ? Why are they carried out ?*
2. *Write short notes on substitution test, capacitance test and compensation test.*

8.19 Reliability Tests

The newly manufactured circuit breakers are tested by type tests and routine tests. But the conditions during these tests are not the conditions that exist at the field. At site the circuit breaker is subjected to various stresses due to,

a) Variation in ambient temperatures.

b) Extremely low and high temperatures.

c) Rain moisture.

d) Vibrations on account of earthquakes.

e) Dust and chemical fumes.

f) Overloads and over voltages.

Also the maintainance of the breaker may not be done by skilled persons. Thus the performance of the breaker is tested under these adverse conditions by reliability tests. The circuit breaker is subjected to extremely high temperature created in test chambers. The various parts are critically examined after testing.

Review Question

1. *Name the various types of reliability tests.*

8.20 Commissioning Tests

These test are performed after the proper installation of the breaker at the site. The operational readiness and proper assembly is verified. High accuracy is not generally expected in such tests. The test facilities available at site is also important factor.

These include following tests,

a) Mechanical operation tests.

b) Measurement of travel, simultaneous touching of contacts.

c) Measurement of insulation resistance and DC resistance.

d) Checking the operation by energising of relays.

e) Checking the operation by energising the manual operating signal.

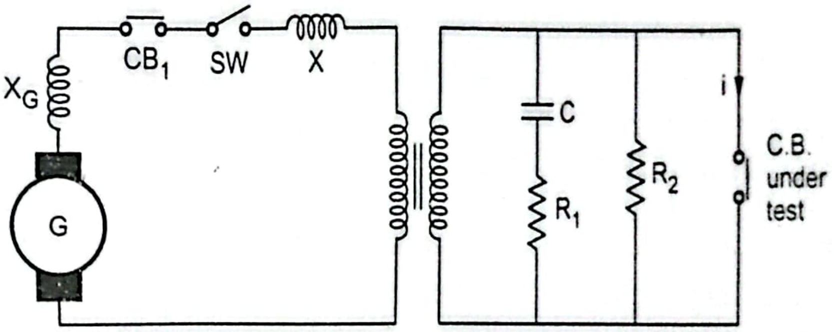
Review Question

1. *List various types of commissioning tests carried out on circuit breakers.*

8.21 Direct Testing

AU : May-14

In direct testing, a circuit breaker is subjected to full power or stress. The circuit for direct testing of single phase circuit breaker is shown in the Fig. 8.21.1.



Transformer T

Fig. 8.21.1

G is a generator generating voltage V_G with reactance X_G. CB_1 is back up or master circuit breaker. X is the current controlling reactance. SW is the making switch while T is the transformer. C, R_1 and R_2 are capacitance and resistances for adjusting the transient recovery voltage.

The transformer is used to obtain proper test voltage. During actual testing, many of the operations are performed in sequence and total time for these operations is too small to have mannual operation. The sequential switching circuitry is useful here. A sequence switch is a drum type switch with several pairs of contacts and is rotated by a motor. When the drum is rotated, there is opening and closing of various control circuits as per the sequence. The sequential operations include making off drive motor of short circuit generator, switching on impulse excitation, closing of master circuit breaker, oscillograph circuit connected, closing of make switch, opening of circuit breaker under test, opening of master circuit breaker, switching off the exciter etc. The operations involved in the above test are performed by means of a sequence switch.

For breaking capacity, master circuit breaker and cirucit breaker under test are closed first. By closing the swtich SW there is a short circuit and the circut breaker under test is opened at desired instant. The breaking current is then determined from the oscillograph.

Making capacity is also an important test which is the ability of a breaker to make on to a short cirucit. The master circuit breaker and switch SW is closed first. The circuit breaker under test is closed on a three phase short circuit to determine making current.

Operating duty tests are performed on the circuit breaker as per standard specifications or according to client's instructions.

Review Questions

1. *Write a note on direct testing of circuit breakers.*
2. *Write short note on : Testing of circuit breakers.*
3. *Briefly describe the different types of testing schemes of circuit breakers.*

AU : May-14, Marks 16

8.22 Short Circuit Test Layout

The short circuit testing is an experimental method for proving the ratings of the breaker and checking its performance for further developments. Many of these tests come under type tests. By carrying out experimentation and problems related to circuit breaking, the modern EHV (Extra High Voltage) breakers are developed.

Due to short circuits, severe stresses are produced on circuit breakers. The circuit breaker must be capable of withstanding the stresses. The short circuit current duration is about 1 sec or 3 sec. The short time current test verify the capability of breaker.

Due to short circuit, thermal stresses are produced on contacts and current carrying parts. The stress is also produced on insulation. The poles and terminals experience electro-dynamic forces.

The making capacity checks the ability of breaker to close on short circuit. The breaker should be capable of closing effectively without contact welding. The breaking capacity verify the ability to clear short circuits. The operating mechanism and the interrupter should able to perform these functions efficiently.

The stresses developed during short circuit depend on magnitude of fault current and design of breaker. After current zero, the contact space is subjected to TRV. Therefore for reliable operation and performance of circuit breaker on short circuit, short circuit testing plants are specially built.

8.22.1 Short Circuit Testing Plants

There are three types of testing stations which are as follows,

a) Field type testing station where power required for testing is taken directly from large power system and the breaker under tests is connected.

b) Laboratory type testing station where the short circuit generators provide the power for testing. The breaker may be tested directly or indirectly.

c) Composite testing station which is a combination of field type testing station and laboratory type testing station.

8.22.2 Layout of a Short Circuit Testing Station

It is represented in the Fig. 8.22.1. The short circuit generators provide the power required. There may be two or more generators though in the figure shown it is only one. Three phase induction motor drives the generator and impulse excitation is provided.

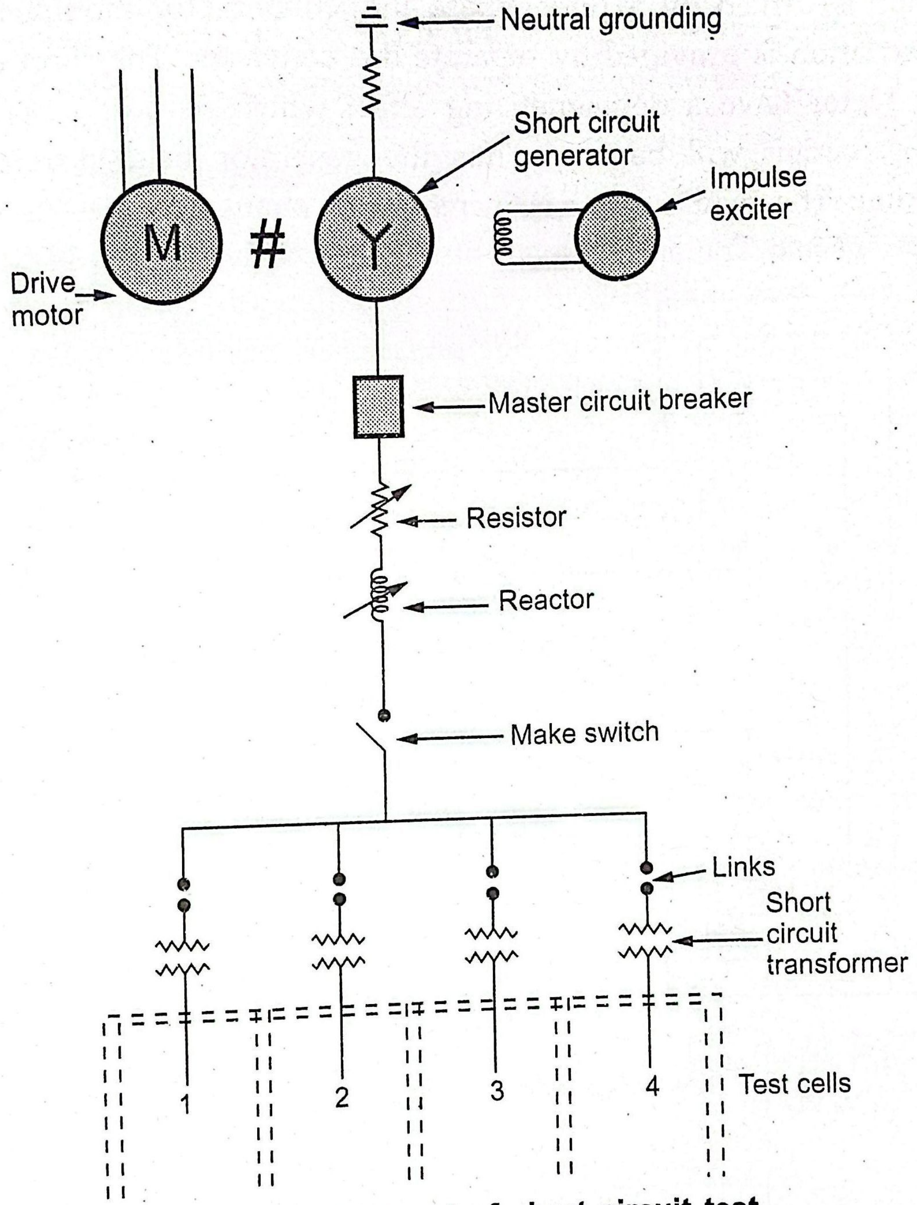

Neutral grounding
Short circuit generator
Impulse exciter
M
#
Y
Drive motor
Master circuit breaker
Resistor
Reactor
Make switch
Links
Short circuit transformer
1
2
3
4
Test cells

Fig. 8.22.1 Layout of short circuit test

For adjusting magnitude of short circuit current, variable series resistors and reactors are provided. The master circuit breaker has higher capacity than the breaker under test. If breaker under test fails to operate, then master breaker operates to protect the circuit. Making switch is a closing device specially designed which can close at desired moment and carries the making currents.

The test voltages are obtained by transformers. These single phase units are connected in various ways to get different test voltages. This also includes some equipments necessary for measurement, record and control, and auxiliary equipments with a sequence switch to obtain sequential operation.

8.22.3 Short Circuit Generator and Drive Motor

The circuit breakers under test are supplied power with this generator. The generator must withstand high reactive power surges for short duration. Their design is therefore somewhat different from conventional alternators.

The generator is driven by a three phase induction motor mounted on same shaft. The impulse excitation is provided by separate d.c. converter. The short circuit current at lagging power factor have a demagnetizing effect which reduces e.m.f. So the voltage before the short circuit will be less. Thus the generator field current is boosted by impulse excitation. The field current is increased to about 10 times its normal value at the time of short circuit. The arrangement of circuit is shown in the Fig. 8.22.2.

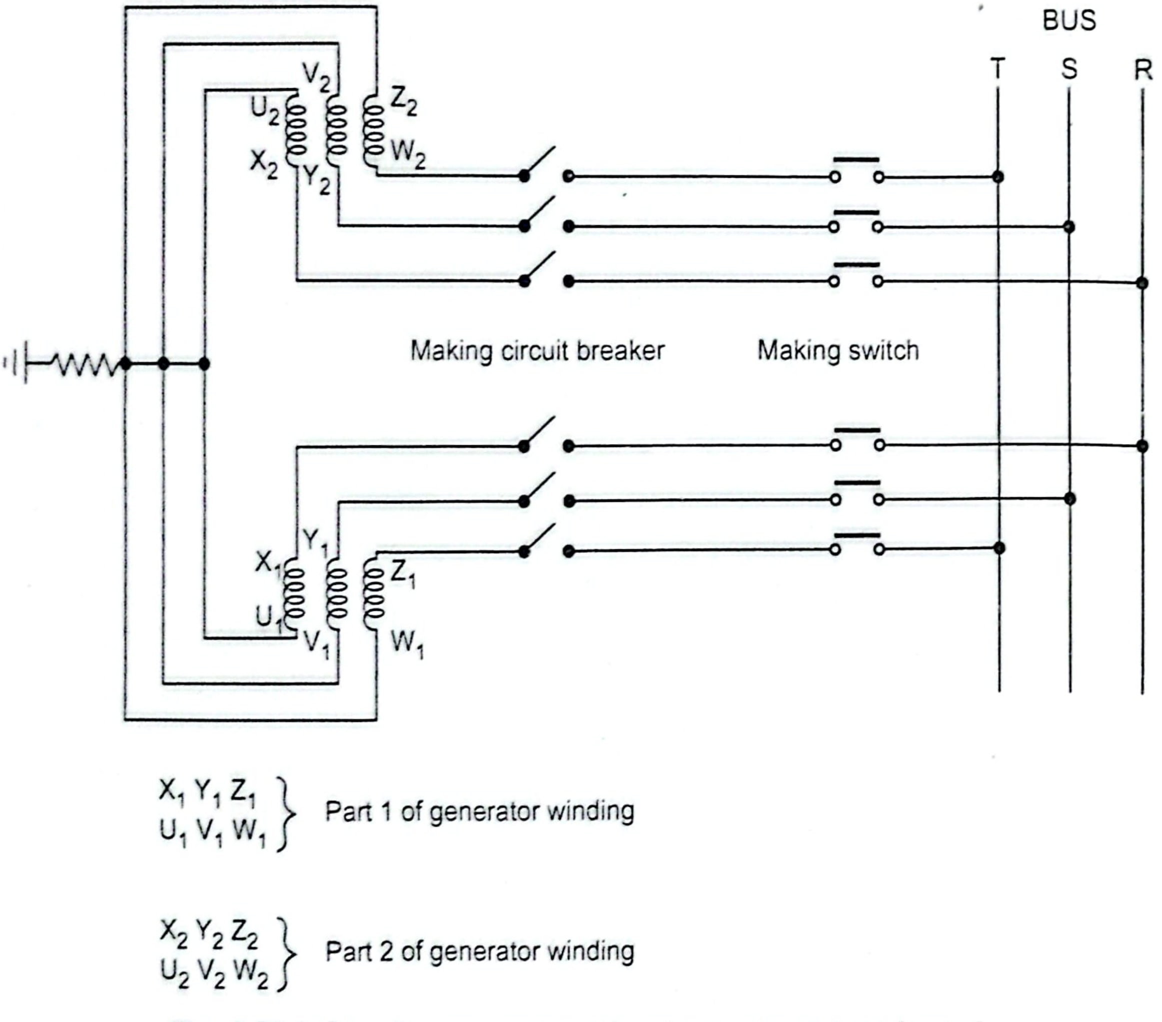

BUS
T
S
R
V_2
U_2
Z_2
X_2
W_2
Y_2
Making circuit breaker
Making switch
Y_1
X_1
Z_1
U_1
V_1
W_1
X_1 Y_1 Z_1 U_1 V_1 W_1 } Part 1 of generator winding
X_2 Y_2 Z_2 U_2 V_2 W_2 } Part 2 of generator winding

Fig. 8.22.2 Circuit arrangement in short circuit test layout

8.22.4 Short Circuit Transformers

The transformers are used for testing the breaker at the voltages other than generator voltage. Three phase transformer is used to step down the voltage whereas single phase transformer is used to step up the voltage. The transformers are designed to withstand repeated short circuit. The leakage reactance of these transformers is kept low. Extra turn insulation is provided to the mechanically strong windings. Cooling is not a severe problem as transformer is not there in a circuit for a long time. As single three phase units becomes big it is not normally used.

8.22.5 Reactors

Reactors are connected in order to control the short circuit current. These are air cored and air cooled. Iron parts are normally absent. It may be single phase or three phase unit. The reactors must be capable of withstanding stresses.

8.22.6 Master Circuit Breaker

This is a air blast type of breaker having capacity more than breaker under test. It operates if breakers under test fail to operate. In addition after every test it isolates specimen under test from supply. It must be able to carry full short circuit current.

8.22.7 Making Device

The short circuit currents are applied correctly at desired moment by this switch. It should have high making capacity while breaking capacity is negligible. It must be air blast making switch with air pressure 14 - 16 kgf/cm^2.

8.22.8 Capacitor

Capacitor banks provide leading current for verifying the performance of breaker for interruption of charging currents. The frequency of the transient recovery voltage $\left(f_n = \frac{1}{2\pi\sqrt{LC}}\right)$ is regulated. In synthetic testing it is an important element.

8.22.9 Resistors

The short circuit p.f. varied by using resistors in series with reactors. It can be increased from 0.1 to 0.3.

8.22.10 Test Cubicles

These are constructions of reinforced cement concrete or strong brick work. In the cubicles the breakers are tested. Separate cubicles are provided for testing L.V., H.V. and EHV equipments.

8.22.11 Sequence Switch

During short circuit testing, many operations are performed in a sequence and total time is very less to perform manual operation. A sequence switch performs the sequential operations as it is a drum switch with several contacts which is rotated by a motor. Due to rotation of drum, control circuits are opened or closed as per specific sequence. The sequences for breaking capacity test in one test are as follows which takes nearly 0.2 seconds,

i) Drive motor of short circuit generator made off.

ii) Impulse excitation switched on.

iii) Master circuit breaker closed.

iv) Oscillogram circuit connected.

v) Make switch closed.

vi) Circuit breaker under test opened.

vii) Master circuit breaker opened.

viii) Excitor switched off and its field supressed.

8.22.12 Different Measurements

Since the test events takes very short time, all measurements must be recorded by oscillographs. Light beam oscillograph which are easily operated are used for slow varying quantities like current, voltage, contact travel or trip signal etc. TRV phenomenon requires only 1 msec. For recording such fast quantities, CRO is used.

The following quantities are recorded during the test,

i) Short circuit current in each phase.

ii) Voltage across each pole before, after and during short circuit.

iii) Fluid pressure.

iv) Contact travel speed.

v) Generator voltage.

vi) TRV.

vii) Current in trip circuit.

Review Question

1. *Explain the short circuit test layout.*

8.23 Indirect Testing

AU : May-07, Dec.-14

It is possible that the short circuit power that can be obtained from the testing station may be insufficient to test a breaker of high capacity. Even a single pole of a EHV breaker cannot be tested by direct means.

The EHV circuit breaker consists of many arc interrupter units which are separately tested called **unit testing.** If one unit is tested, the capacity of complete pole and breaker is determined. This method of unit testing is adopted internationally.

Synthetic testing is another popular method which permits testing of breaker.

8.23.1 Unit Testing

The modern EHV circuit breakers contains two or more similar interrupters per pole. These interrupters operate simultaneously and share the voltage across the pole equally. The breaking capacity is also equally shared. The results obtained on one unit can be extended further for total capacity of breaker. This is known as **unit testing** or **element testing.** It is internationally accepted method.

During the application of unit test, the voltage must be reduced by a factor b so the corresponding impedances are also reduced by b to get test voltage across the unit by following expression.

$a = \frac{1}{m}$ where m = Number of units per pole and one unit is tested.

$a = \frac{n}{m}$ where n units are tested

Let us consider the examples of a 3 pole, 220 kV breaker with 3 units per pole

$$\text{Voltage across one pole} = \frac{220}{\sqrt{3}} = 127 \text{ kV}$$

$$a = \frac{1}{m}; \quad m = 3 \quad \therefore \quad a = \frac{1}{3}$$

$\therefore$ Voltage required for testing one unit = a × Voltage per pole $= 127 \times \frac{1}{3} = 42.33$ kV

L and C of the test circuit is also reduced to get same natural frequency as that of direct testing.

In direct test, Natural frequency, $f_n = \frac{1}{2\pi\sqrt{LC}}$

In unit testing, $f_n = \frac{1}{2\pi\sqrt{aL \times \frac{C}{a}}} = \frac{1}{2\pi\sqrt{LC}}$

The natural frequency of TRV remains unchanged. Time scale also remains unchanged.

If voltage distribution across the pole is uneven then some units will be stressed more while other will be stressed less. The unit that is undergoing highest stress must be tested. This is reliable method of testing.

8.23.2 Synthetic Testing

It consists of current source and voltage source with relatively low voltage and low current respectively. The principle of synthetic testing can be explained from the Fig. 8.23.1.

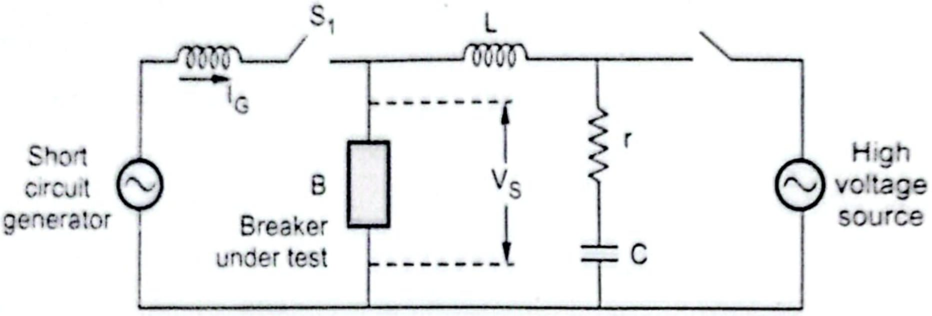


Fig. 8.23.1

The current source provides short circuit current. The voltage source provides restriking voltage and recovery voltage. The test conditions are given by L, r, C. The short circuit current I_G is supplied by closing switch S_1. At final current zero, switch S_2 is closed and voltage contains transient as it contains L and C.

The advantages of this method are as follows,

i) The breaker can be tested for desired TRV and RRRV.

ii) The short circuit generator has to supply currents at less voltage.

iii) The flexibility can be obtained by independent control of test current and test voltage.

iv) As method is simple it can be applied to unit testing also.

v) A breaker having capacity five times that of plant can be tested.

Review Questions

1. *What is indirect testing of circuit breakers ?*
2. *What is unit testing and synthetic testing of circuit breakers ?*
3. *Explain briefly synthetic testing of circuit breaker.*
4. *With a circuit diagram and waveform, explain synthetic testing an HV circuit breaker.* **AU : May-07, Marks 8**
5. *Write notes on : i) Unit testing ii) Synthetic testing.*
6. *Explain the procedure adopted in unit test and synthetic testing of circuit breaker.*
7. *What are the different methods of testing of circuit breakers ? Describe the method which is more suitable for testing the large capacity circuit breakers. Also, discuss the merits and demerits of the method.* **AU : Dec.-14, Marks 16**

8.24 Types of Synthetic Test Circuits

There are two types of synthetic test circuits

i) Parallel current injection ii) Series current injection.

8.24.1 Parallel Current Injection Method

This method is used for testing breakers as it gives high frequency transient voltages as required by standards. It is shown in the Fig. 8.24.1.

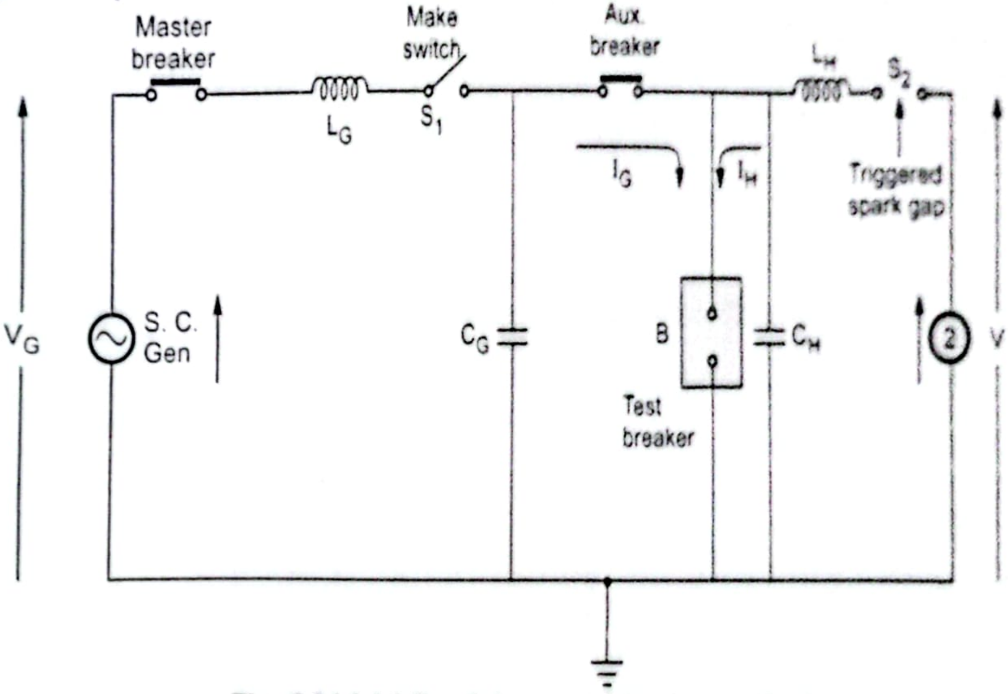

Master breaker
Make switch
Aux. breaker
L_H
S_2
L_G
S_1
I_G
I_H
Triggered spark gap
V_G
S. C. Gen
C_G
B
C_H
2
V
Test breaker

Fig. 8.24.1 (a) Parallel current injection method

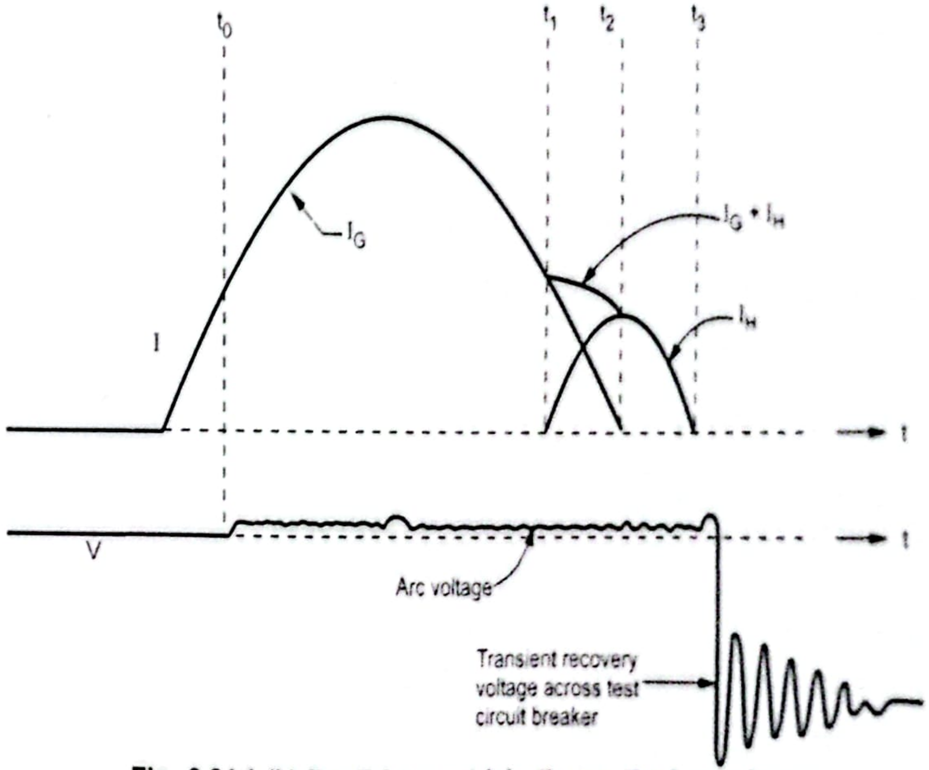


Fig. 8.24.1 (b) Parallel current injection method waveforms

In this method the voltage circuit (2) is effectively connected in parallel with current circuit (1) and test breaker before main current I_G in test breaker current is properly simulated.

8.24.2 Series Current Injection Method

The Fig. 8.24.2 represents series current injection method. The voltage circuit (2) is connected to current circuit in series before main current zero. Due to this I_G and I_H are in opposition. The stresses produced in the synthetic test and those in actual network must be same but it is not the actual case because of several factors like high current, high voltage, instant of applying voltage etc. (See Fig. 8.24.2 (b) on next page)

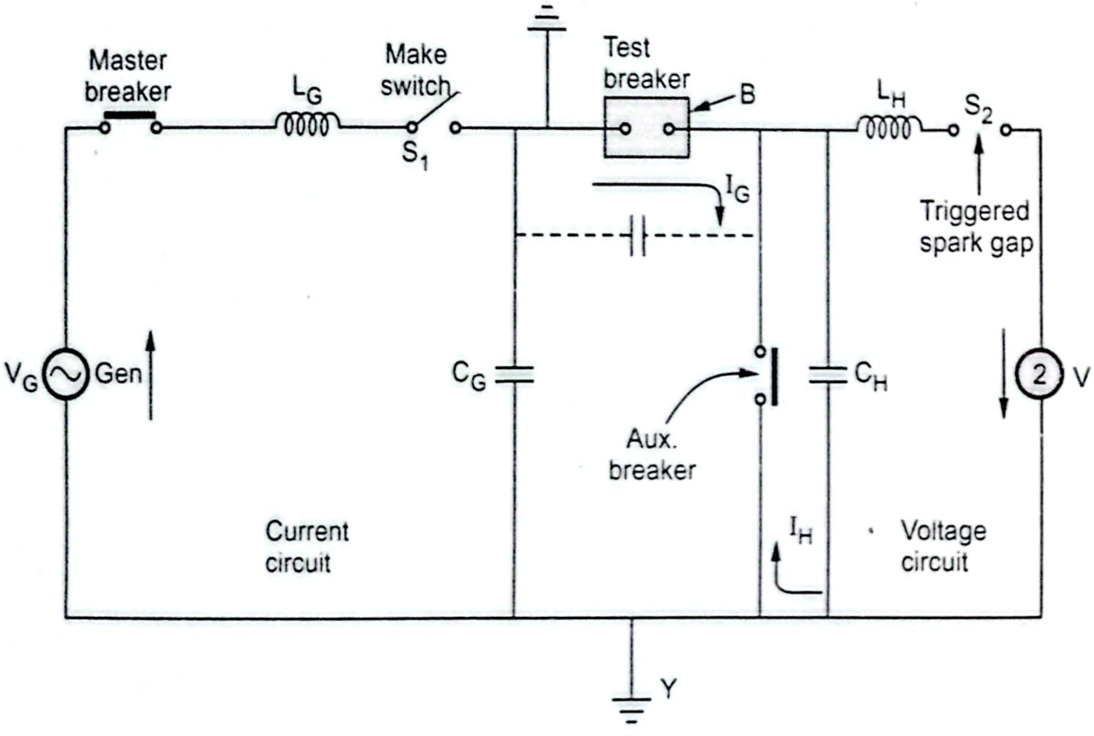


Fig. 8.24.2 (a) Series current injection method

8.24.3 Brown Boveri's Synthetic Testing Circuit

This circuit is shown in the Fig. 8.24.3. The short circuit current is supplied from low voltage circuit. The restriking and recovery voltage is supplied by different high voltage circuit. (See Fig. 8.24.3 on next page.)

The high current circuit on left side consists of short circuit generator G, short circuit transformer with resistor R_G and capacitor C_G which controls natural frequency of current. The short circuit power is supplied at voltages V_S which corresponds to about 30 kV which is smaller than recovery voltage required for testing. The recovery voltage is supplied by high voltage circuit on right side.

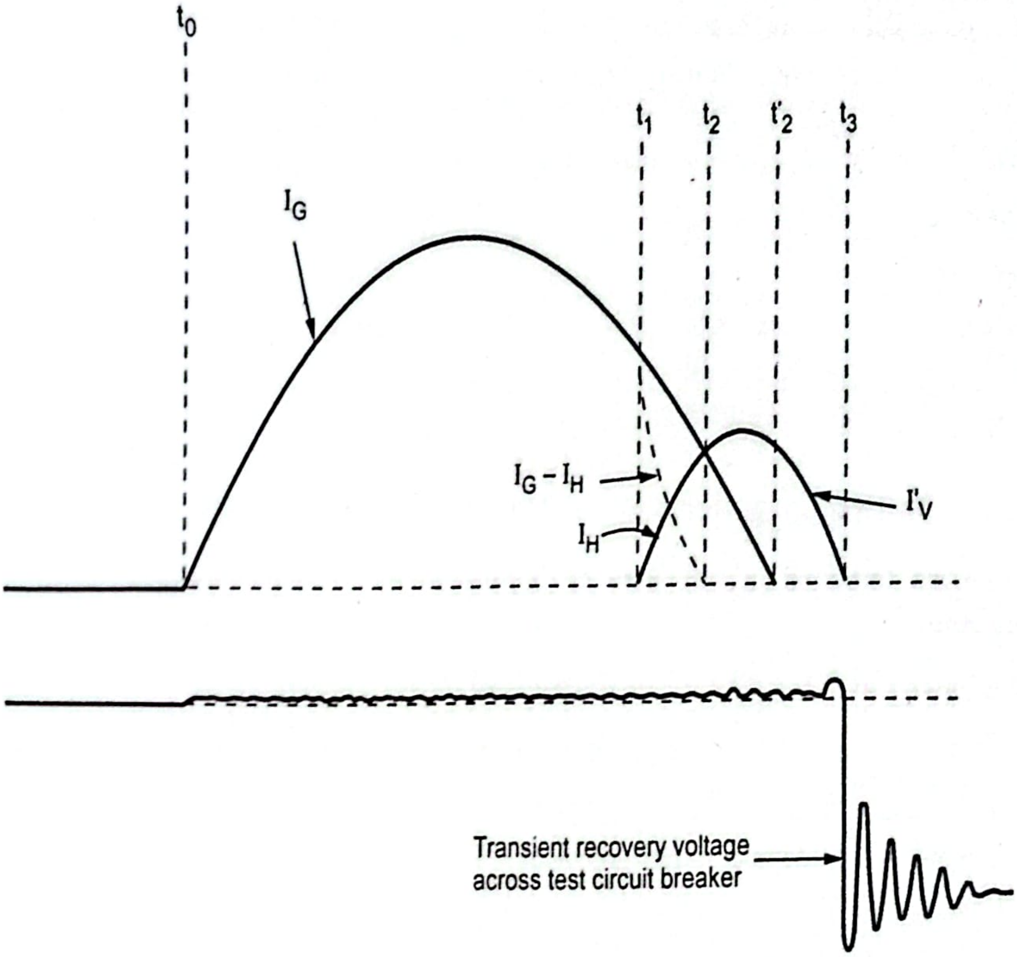


Fig. 8.24.2 (b) Series injection method waveforms

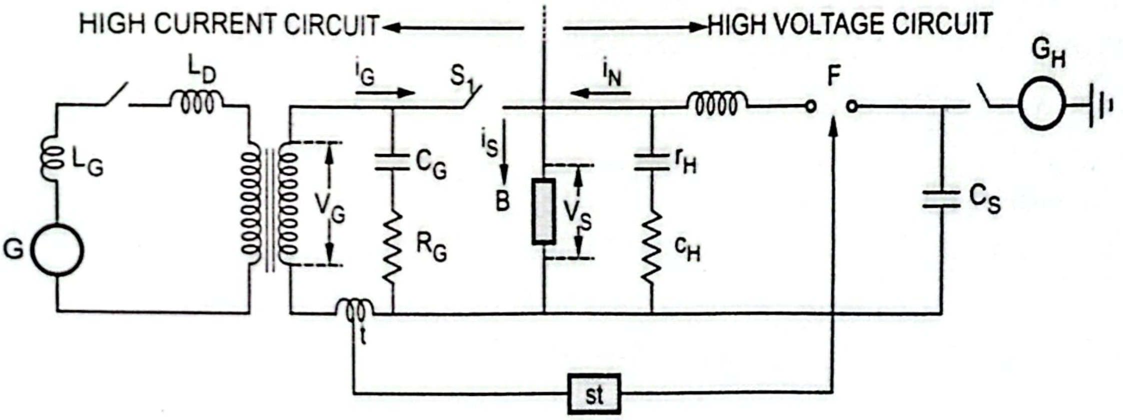

HIGH CURRENT CIRCUIT
HIGH VOLTAGE CIRCUIT
L_D
i_G
S_1
i_N
F
G_H
L_G
G
C_G
V_G
R_G
i_S
B
V_S
r_H
c_H
C_S
t
st

Fig. 8.24.3 Brown Boveri's synthetic testing circuit

The test breaker and auxiliary breaker S_1 are opened together. Before the current interruption takes place in breaker B, the spark gap is triggered by control S_t and voltage V is applied to breaker B. During final current zero only current i_H flows through breaker B. Previously $i_S = i_G + i_H$ which is interrupted by S_1 and breaker B. But now breaker B has to interrupt only i_H. Hence restriking voltage across breaker B is given by HV circuit.

Review Questions

1. *Explain parallel current and series current injection methods of synthetic testing.*
2. *With a neat sketch explain synthetic testing (parallel current injection method) of circuit breakers.*
3. *Mention the different types of tests that are performed on a circuit breaker. Explain the parallel current injection method of synthetic testing of a circuit breaker.*
4. *With neat circuits, explain briefly the two types of synthetic test on circuit breaker.*
5. *Explain any one type of synthetic testing of circuit breaker.*

8.25 Two Marks Questions with Answers

Q.1 Mention three major duties to be performed by a circuit breaker under short circuit.

Ans. : Following are the three major functions of circuit breaker.

1. The fault current must be safely interrupted by the circuit breaker.
2. The faulty section of the system must be isolated by circuit breaker as quickly as possible keeping minimum delay.
3. The faulty circuit only must be isolated without affecting the healthy one.

Q.2 Differentiate between a symmetrical and asymmetrical breaking current.

Ans. : Symmertical breaking current : This is the r.m.s. value of a.c. component of the current in the pole at the instant of contact separation.

$$I_{\text{symmetrical}} = \frac{I_{ac}}{\sqrt{2}}$$

Asymmetrical breaking current : This is the r.m.s value of the total current consisting of a.c. and d.c. component of the current in the pole at the instant of contact separation.

$$I_{\text{asymmetrical}} = \sqrt{\left(\frac{I_{ac}}{\sqrt{2}}\right)^2 + (I_{dc})^2}$$

Q.3 What is the advantage of cross jet explosion pot in oil circuit breaker ?

Ans. : The cross-jet explosion pot gives satisfactory performance at heavy fault currents. As the arc is struck, the gases formed exerts increased pressure which gives a more powerful blast and greater electrical strength per unit length.

Q.4 State the arcing in SF_6 medium. **AU : May-13**

Ans. : The contacts of the breaker are opened in a high pressure flow of SF_6 gas and an arc is struck between them. The conducting electrons from the arc are captured by the gas to form relatively immobile negative ions. The loss of these conducting electrons develops enough strength of insulation which will extinguish the arc. Thus

SF_6 circuit breakers are found to be very effective for high power and high voltage service and widely used in electrical equipments. Only the care to be taken is that some by-products are produced due to breakdown of gas which are hazard to the health of the personnel and it should be properly disposed.

Q.5 What are the main design problems in HVDC circuit breakers ?

Ans. : The two major problems of HVDC circuit breaking are,

i) The natural zero current does not occur as in the case of a.c. circuit breakers.

ii) The amount of energy to be dissipated during the short interval of breaking is very high as compared to the conventional a.c. circuit breakers.

Q.6 Enumerate the chief requirements of the contact material for vacuum circuit breaker.

Ans. : The chief requirement of the contact material for vacuum circuit breaker are,

i) It should have good electrical conductivity to pass normal load currents without overheating.

ii) It should have good thermal conductivity to dissipate rapidly large heat generated during arcing.

iii) It should have high density, high thermionic function to enable arc extinction, high boiling point to reduce arc erosion. Low gas content to ensure longer service life and sufficient mechanical strength to retain structural integrity under high voltage gradiants at the surface.

iv) It should have high cold and hot hardness to prevent wear and tear during normal opening and closing operations.

Q.7 What are the chief disadvantages of oil as an arc quenching medium in circuit breakers ?

Ans. : The chief disadvantages of oil as an arc quenching medium in circuit breakers are,

i. Oil may be flammable and can cause fire hazards.

ii. There is a risk of formation of explosive mixture with the air.

iii. Due to the decomposition of the oil in the arc, the oil becomes polluted by carbon particles, which reduces its dielectric strength. Hence periodical maintenance and replacement of oil is required.

Q.8 Write any two merits of vacuum circuit breakers. **AU : Dec.-14**

Ans. : Merits of vacuum circuit breakers are,

i. They are compact in size and have longer life.

ii. There are no fire hazards.

iii. There is no generation of gas during and after operation.

iv. There is no restriction on interruption of fault current. This is outstanding quality of vacuum circuit breaker.

Q.9 List the routine tests conducted on circuit breakers.

Ans. : The routine tests conducted on circuit breakers are

i. Mechanical operation tests.

ii. Millivolt drop test, measurement of resistance.

iii. Power frequency voltage tests.

iv. Voltage tests on auxiliary circuits, control circuits.

Q.10 What is the special feature of vacuum circuit breaker ?

Ans. : In vacuum type of circuit breakers, vacuum is used as the arc quenching medium. It is superior medium than any other arc quenching medium as vacuum offers highest insulting strength.

If we consider that the contacts of circuit breakers are opened in vacuum, the interruption occurs at first current zero. The dielectric strength of the contact space builds up very rapidly at a rate which is very much higher than that with other circuit breakers.

Q.11 What is self compensated explosion pot ?

Ans.: It is essentially combination of plain explosion and cross explosion type. Hence it can interrupt low as well as heavy short circuit currents effectively.

Q.12 What are the types of circuit breakers ? **AU : Dec.-14**

Ans. : The various types of circuit breakers are,

i) Air blast circuit breaker

ii) Air break circuit breaker

iii) Vacuum circuit breaker

iv) SF_6 circuit breaker

v) Bulk oil circuit breaker

vi) Minimum oil circuit breaker.

Q.13 Write advantages of SF_6 circuit breaker. **AU : May-13, 15**

Ans. : The advantages of SF_6 circuit breaker are,

i. SF_6 gas is noninflammable and chemically stable, decomposition products are not explosive hence no danger of fire.

ii. Same gas is recirculated in the circuit hence requirement of gas is small.

iii. Ample overload margin : For the same size of conductors, current carrying ability of SF_6 circuit breaker is about 1.5 times than that of air blast circuit breaker because of more heat transferability.

iv. The breaker is silent in operation and does not make sound like air blast circuit breaker due to its closed gas circuit.

v. Sealed construction avoids contamination by moisture, dust etc. There are no carbon deposites.

Q.14 How does a circuit breaker differ from a switch ? **AU : Dec.-15**

Ans. : A switch is meant only for opening and closing of circuit with normal current. It is not capable of interrupting fault current. A circuit breaker is a protective device which can make or break a circuit either manually or automatically under no load, full load or short circuit conditions. Arc interrupting mechanism is absent in a switch while it is present in a circuit breaker. A switch is normally operated in open circuit or at no load conditions while a breaker may be operated at no load or at load condition.

Q.15 What is meant by rupturing capacity of a circuit breaker ?

Ans. : Breaking capacity or rupturing capacity is the current that a circuit breaker is able to interrupt without being destroyed or causing an electric arc with unacceptable duration. It is the product of breaking current and the recovery voltage.

Q.16 What are the basic requirements of circuit breakers ?

Ans. : The basic requirements of circuit breakers are,

i. The normal working current and the short circuit current must be safely interrupted by the circuit breaker.

ii. The faulty section of the system must be isolated by circuit breaker as quickly as possible keeping minimum delay.

iii. It should not operate with flow of overcurrent during healthy conditions.

iv. The faulty circuit only must be isolated without affecting the healthy one.

Q.17 Write any two disadvantages of SF_6 circuit breaker. **AU : Dec.-22**

Ans. : The disadvantages of SF_6 circuit breaker are,

i. Sealing problem arises due to the type of construction.

ii. Imperfect joint lead to leakage of gas.

iii. The presence of moisture in the system is very dangerous.

iv. Double pressure SF_6 circuit breakers are relatively costly due to type of construction and complex gas system.

v. Internal parts should be cleaned thoroughly during periodic maintenance under clean and dry environment.

vi. Special facilities are needed for transporting the gas, which is very costly.

Q.18 List the type tests conducted on circuit breakers. **AU : May-08**

Ans. : The type tests conducted on circuit breakers are,

i. Mechanical tests.

ii. Tests of temperature rise, millivolt drop test.

iii. High voltage test.

iv. Basic short circuit test.

   a. Making test

   b. Breaking test

   c. Operating sequence tests at 10 %, 30 %, 60 %, 100 % of rated breaking current with specified TRV conditions.

v. Critical current tests.

vi. Single phase short circuit test.

vii. Short time current test.

Q.19 What is dielectric test of a circuit breaker ?

Ans. : The basic design of circuit breaker which includes the clearances, bushing materials, correctness and accuracy in assembly and the quality of materials used has in general effect on the dielectric characteristics of any circuit breaker. For a given circuit breaker, these factors can be checked from the point of view of their ability to withstand overvoltages at the normal service voltage and abnormal voltages during lightning.

In these tests, a test voltage is applied for duration of 1 minute between phases with the breaker closed, between phase and earth with circuit breaker open and across the breaker terminals under breaker open. During this test, there must not be flashover or puncture of the breaker.

The wave of μsec duration with voltage magnitude based on voltage rating of breaker is applied in this test. For non-effectively grounded system, higher impulse voltage is specified than in case of solidly grounded systems. The breaker should withstand this voltage without flashover.

In wet dielectric tests, carried out on outdoor switchgears, the external insulation is sprayed for 2 minutes while the rated service voltage is applied. The test overvoltage is then maintained for about 30 seconds and flashover should not occur.

Q.20 What are the types of tests carried out on circuit breakers ? **AU : May-15**

Ans. : The types of tests carried out on circuit breakers are,

i) Type tests
ii) Routine tests
iii) Development tests
iv) Commissioning tests
v) Dielectric tests
vi) Reliability tests.

Q.21 How do you classify circuit breakers ?

Ans. : The circuit breakers are classified by various ways. The different criteria for classification of circuit breakers are as follows,

i) Interrupting medium
ii) According to service
iii) Way of operation
iv) Action

v) Method of control
vi) Way of mounting
vii) Tank construction
viii) Contacts.

Q.22 Enumerate the breaking or rupturing capacity of circuit breakers.

AU : Dec.-14, May-17

Ans. : Breaking capacity or rupturing capacity is the current that a circuit breaker is able to interrupt without being destroyed or causing an electric arc with unacceptable duration. It is the product of breaking current and the recovery voltage.

Q.23 Write the operational difference between fuse and circuit breaker ?

Ans. : The fuse element needs to be replaced after every operation which is not the case with circuit breaker. Fuses tend to be quicker to interrupt the flow of power, but must be replaced after they melt, while circuit breakers can usually simply be reset.

The working of fuse is based on the electrical and thermal properties of the conducting material, while that of a circuit breaker is based on the electromechanical principles. Fuses offer protection against only power overloads, while circuit breaker offers protection against power overloads and short circuits.

Q.24 Write the ratings of the circuit breakers. **AU : Dec.-13**

Ans. : The ratings of the circuit breakers are

i) Rated voltage.
ii) Rated insulation level.
iii) Rated normal current.
iv) Rated frequency.
v) Rated duration of short circuit.
vi) Rated short circuit breaking current.
vii) Rated short circuit making current.
viii) Rated peak withstand current.
ix) Rated TRV for terminal fault.
x) Rated operating sequence.
xi) Rated supply voltage for opening and closing devices and auxiliary circuits.
xii) Rated pressure of compressed gas for interruption.

Q.25 Give the difference between isolator and circuit breaker. **AU : May-13**

Ans. :

Sr. No.	Isolator	Circuit breaker
1.	It is designed to isolate a circuit or other component after the decay of current in the circuit.	It is designed to break a circuit carrying current under faulty conditions and make and break the current under normal operating conditions.
2.	It is only a switching device.	It is switching as well as protective device.
3.	It does not have any mechanism for arc extinction.	It provides medium for arc extinction.

4.	It is operated under no load condition.	It can be operated under load condition.
5.	Arc is not formed during separation of contacts.	Arc is formed during separation of contacts which needs to be extinguished quickly.

Q.26 Compare MOCB and bulk oil circuit breaker. **AU : May-22**

Ans. :

Sr. No.	Minimum oil circuit breaker (MOCB)	Bulk oil circuit breaker
1.	This circuit breaker uses minimum quantity of oil.	Large quantity of oil is used.
2.	Reduced risk of fire.	Increased risk of fire.
3.	Maintenance is comparatively easier.	Suffers from maintenance problems.
4.	It is comparatively cheaper due to use of minimum quantity of oil.	It is costlier as it uses more quantity of oil.
5.	Space requirement is lowered.	Larger space is required.
6.	The degree of carbonization is high.	The degree of carbonization is less due to use of large quantity of oil.

Q.27 Define the operating time of circuit breaker. **AU : May-14**

Ans. : The operating time of circuit breaker is sum of opening time and the arcing time where opening time is time passed between the energization of the trip coil to the instant of contact separation while the arcing time is the time interval from contact separation to the extinction of arc.

Q.28 Write the differences between the fuse and circuit breaker. **AU : May-14**

Ans. :

Sr. No.	Fuse	Circuit Breaker
1.	It works on thermal and electrical properties of the conducting material.	It works on electromechanical principles.
2.	It can not be reused once used. It is required to be replaced.	It can be reused after correction of fault in the system.
3.	It provides protection against power overloads.	It provides protection against power overloads as well as short circuits.
4.	It is cheaper.	It is expensive.

Q.29 What is meant by making capacity of a circuit breaker ? **AU : Dec.-15**

Ans. : The peak value of first current loop of short circuit current which the circuit breaker is capable of making at its rated voltage is called making capacity of a circuit breaker.

The rated making current capacity of a circuit breaker is 2.55 times the rated short circuit breaking capacity of a circuit breaker.

Q.30 Define rated short circuit breaking current and capacity of a circuit breaker.

AU : Dec.-15, 17

Ans. : It is r.m.s. value of highest short circuit current which the circuit breaker is capable of breaking under specified conditions of TRV and power frequency voltage and expressed in kA r.m.s. at contact separation.

Q.31 Why current chopping is not common in oil circuit breakers ? **AU : Dec.-15**

Ans. : In oil circuit breakers the arc control is proportional to the fault current to be interrupted and the exitinguishing power is proportional to the current to be interrupted. Hence current chopping is not common in oil circuit breakers.

Q.32 Name the materials used for contacts of vacuum circuit breakers. **AU : Dec.-15**

Ans. : The various materials used for the contacts of vacuum circuit breakers are copper-bismuth, silver-bismuth, silver - lead and copper lead.

Q.33 A circuit breaker is rated as 1500 A, 1000 MVA, 33 kV, 3 second, 3 phase oil circuit breaker. Find rated making current. **AU : May - 18**

Ans. :

$$\text{Breaking current} = \frac{VA}{\sqrt{3}\,V_L} = \frac{1000\times10^6}{\sqrt{3}\times33\times10^3} = 17.495\text{ kA}$$

$$\text{Rated making current} = 2.55 \times \text{Breaking current}$$

$$= 2.55 \times 17.495 = 44.612\text{ kA}$$

Q.34 Why oil circuit breakers are not suitable for heavy current interruption at low voltages ? **AU : Dec.-18**

Ans. : In oil circuit breaker, the oil is inflammable and may cause fire hazard. There is possibility of forming explosive mixture with air and the production of carbon particles in the oil due to heating. This reduces the dielectric strength. Hence the oil circuit breakers are not suitable for heavy current interruption due to carbonization of oil.

Q.35 What are the advantages of oil as arc quenching medium ? **AU : May-19**

Ans. : 1. It obsorbs the arc energy to decompose the oil in to gases which have excellent cooling properties.

2. It acts as an insulator and permits smaller clearance between live conductors and earthed components.
3. It presents cooling surface in close proximity to the arc.
4. Oil has high dielectric strength.

8.26 University Questions with Answers (Long Answered Questions)

(Regulation 2013)

Dec.-16

Q.1 *With a neat sketch explain the principle of vacuum circuit breaker.* **[Section 8.8]** **[8]**

May-17

Q.2 *With a neat diagram explain the construction and working principle of air blast circuit breaker and vaccum circuit breaker.* **[Sections 8.5 and 8.8]** **[16]**

Dec.-17

Q.3 *Describe the construction and principle of operation of air blast circuit breaker.* **[Section 8.5]** **[16]**

May-18

Q.4 *Explain the construction, working principle, operation and application of Vacuum circuit breakers.* **[Section 8.8]** **[16]**

Dec.-18

Q.5 *Describe the constructional and operational aspects of cross blast and axial blast Air Circuit Breakers (ACB). Also discuss the meritorious features of ACB over oil circuit breakers.* **[Section 8.5]** **[13]**

May-19

Q.6 *With neat diagram, explain the construction and principle of operation of air blast circuit breaker.* **[Section 8.5]** **[13]**

(Regulation 2017)

May-22

Q.7 *With neat sketch, explain the working of axial air blast type circuit breaker.* **[Section 8.5]** **[13]**

Dec.-22

Q.8 *Explain the construction, operating principles of SF_6 circuit breaker with neat diagram* **[Section 8.7]** **[13]**

Q.9 *Explain with neat sketch the construction, operating principle of minimum oil circuit breaker with its merits and demerits* **[Section 8.12]** **[13]**

❑❑❑

A

Lightning Arresters (Surge Divertors)

Syllabus

Types of lightning arresters.

Contents

A.1 Requirements of Lightning Arrester

A.2 Operation of a Typical Surge Diverter (Lightning Arrester)

A.3 Horn Gap Arrester

4.4 Rod Gap Arrester or Spark Gap Arrester

A.5 Multigap Arrester

A.6 Expulsion Type Arrester

A.7 Thyrite Type (Valve Type) Arrester

A.8 Metal Oxide (ZnO) Type Arrester

A.1 Requirements of Lightning Arrester

The ideal lightning arrester has following requirements.

i) It should not carry any current at normal system voltage i.e. its breakdown voltage should be above any normal or abnormal fundamental frequency voltage that may occur on the system.

ii) The transient voltage wave whose peak value is greater than the spark over or breakdown voltage of lightning arrester should breakdown as fast as possible to provide path for surge to earth.

iii) After the breakdown, the lightning arrester should be capable of carrying discharge current without damage to it and the voltage should not be more than its breakdown value.

iv) When the transient voltage reduces below its breakdown value, the power frequency current flowing through the diverter should be interrupted as quickly as possible.

Review Question

1. *What are requirements of lightning arrester ?*

A.2 Operation of a Typical Surge Diverter (Lightning Arrester)

The basic form of any type of surge diverter is shown in the Fig. A.2.1 (a).

It consists of a spark gap which is in series with a non linear resistor. The terminal of the protected equipment is connected on end of the diverter. The other end of the diverter is solidly grounded through non-linear resistor.

The length of a spark gap is set in such a way that the normal system voltage is not sufficient to initiate arc across the gap while very high voltage will cause break down of air insulation and arc is initiated.

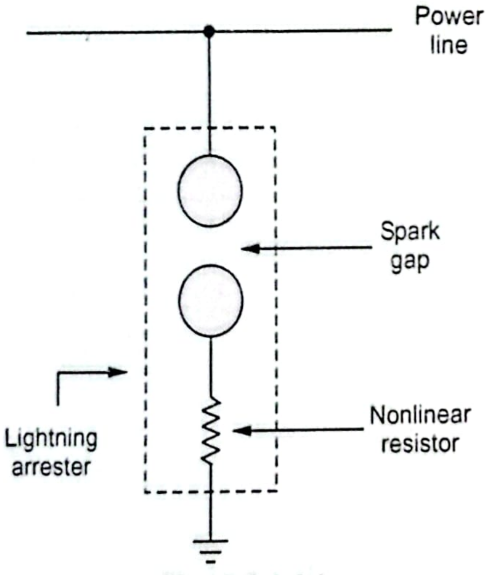


Fig. A.2.1 (a)

The non-linear resistor bears a property of decrease in its resistance as the voltage increases and vice versa. The volt-amp characteristics for a non linear resistor is shown in the Fig. A.2.1 (b).

Under normal condition, the diverter is off without conducting any current or very small negligible current due to capacitive effect (Non-linear resistor offers very high resistance to this current hence it is negligible) Hence the gap is not conducting.

Whenever high voltage occurs, there is breakdown of air insulation initiating the arc. Thus a low resistance path is offered for the surge to the earth. Excess charge on the line because of surge is conducted to the earth through the arrester which prevents the surge being sent back on line.

As there is breakdown of spark gap due to over voltage, the arc would be short circuit on the system and may cause power follow current in the diverter. After the surge is over, the resistor offers very high resistance to prevent the effect of short circuit which makes the spark gap non-conducting.

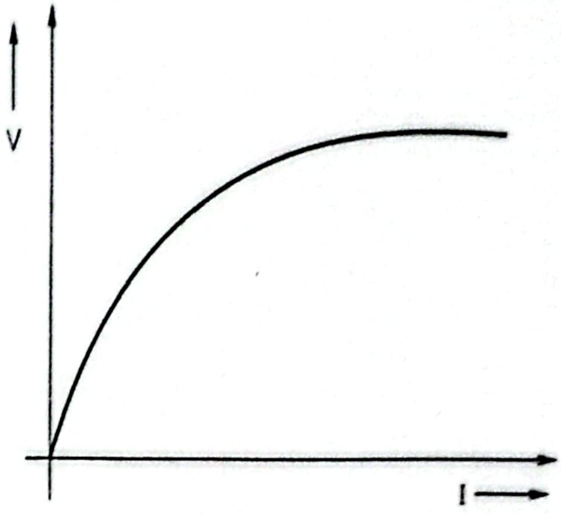


Fig. A.2.1 (b)

It should be observed that the arc in the gap should immediately cease after the surge is over to avoid the current flowing through gap and resistor which would be damaged otherwise. The voltage drop across the arrester should be less than the breakdown strength of the insulation of the equipment to be protected.

Presently following types of surge arresters are commonly used.

1. Valve type or gapped silicon-carbide surge arresters consisting of silicon carbide discs in series with spark gap units.
2. Zinc oxide gapless arresters or metal oxide arresters. These are gapless and consisting of ZnO (Zinc Oxide) discs in series. These arresters are having good volt-amp characteristics. The energy absorption level is also high and these arresters are preferred for EHV and HVDC installations.

Review Question

1. *Briefly discuss the operation of surge diverter.*

A.3 Horn Gap Arrester

This type of arrester has two horn shaped metal rods separated by a small distance. One end is connected to the line while the other is connected to the earth. It is shown in the Fig. A.3.1.

The horns are constructed in such manner that the distance between them gradually increases towards the top. The horns are mounted on porcelain insulators. The resistance R limits the follow current to a small value. The choke connected between equipment to be protected and horn gap is designed in such a way as to offer small reactance at normal power frequency while high reactance at transient frequency. Hence the choke

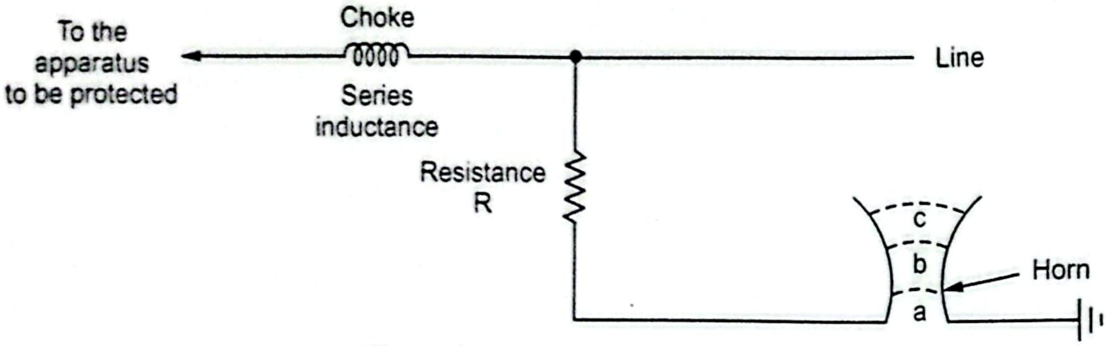


Fig. A.3.1 Horn gap arrester

does not allow any transients to enter the apparatus to be protected. By using the choke the steepness of the wave incident on the equipment to be protected is reduced. While the choke also reflects the voltage surge back on to the horn. The gap between the horns is adjusted in such a way that normal supply voltage will not be sufficient to initiate arc across the gap.

Under normal conditions, the gap is non-conducting whenever there is an overvoltage in the system and its value is more then breakdown value of gap, spark over takes place across small gap. The arc formed may be maintained by the normal voltage also. The heated air around the arc and the magnetic effect of the arc cause it to move up in the gap. The arc acts like a flexible conductor. The arc moves gradually through position a, b, c respectively. At some position (say c), lengthening of arc takes place as distance between the horns is too large. Thus the voltage is not enough to maintain the arc and it is extinguished. The excessive charge on the line is therefore travelled to the earth through the arrester.

A.3.1 Advantages

1. After the surge is over, this type of arrester does not cause short circuiting of the system as the arc is cleared by itself.
2. The follow current is maintained to a small value with the help of series resistance.

A.3.2 Disadvantages

1. If the gap is bridged due to some external factors (such as birds) the device will not work properly.
2. The setting of horn gap is required to be changed due to corrosion and pitting which can affect its performance.
3. The time required for its operation is relatively more (about 3 seconds) than recent fast operating devices.
4. It is harmful to employ this type of arrester on isolated neutral system.

Due to above limitations, the horn gap arrester is rarely used in practice. Also it has low reliability and hence used as secondary protection.

Review Question

1. *Describe the construction, principle of operation and application of horn gap arrester.*

A.4 Rod Gap Arrester or Spark Gap Arrester

It is the simplest, cheapest and most rugged form of surge diverter used for protection of insulators in line, equipments and bushings. It is shown in the Fig. A.4.1.

The conducting rods are provided between the line terminal and earthed terminal of the insulator with an adjustable gap. The medium present in the gap is air. The rods are either square or round with diameter approximately 12 mm and bent at right angles. One rod is connected to the line circuit while the other rod is connected to the earth. The gap between the rods may be in the form of horns or arcing rings.

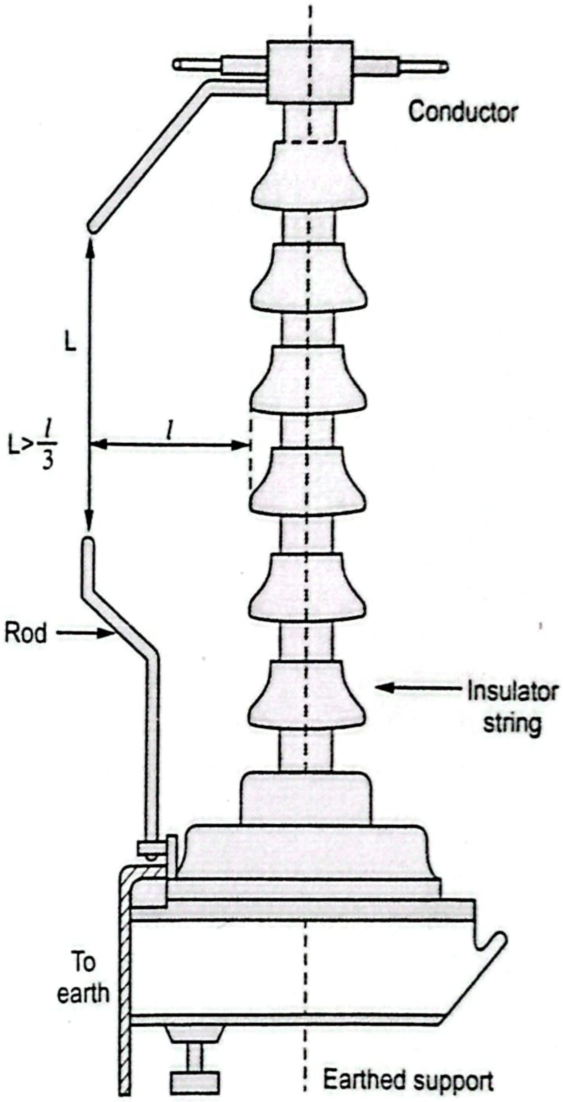


Fig. A.4.1

The gap is adjusted in such a way that the breakdown should occur at about 20 % below flash over voltage of insulator so as to avoid cascading of very steep wave fronts across insulators. The distance between the arc path and insulator should be more than one third of the gap length to prevent the arc from being blown on the insulator. The system operating voltage has the influence on rod gap. It is tabulated below in the Table A.4.1.

Sr. No.	System voltage (kV)	Rod gap (cm)
1	33	22.86
2	66	35.56
3	132	66.04
4	275	124.46

Table A.4.1

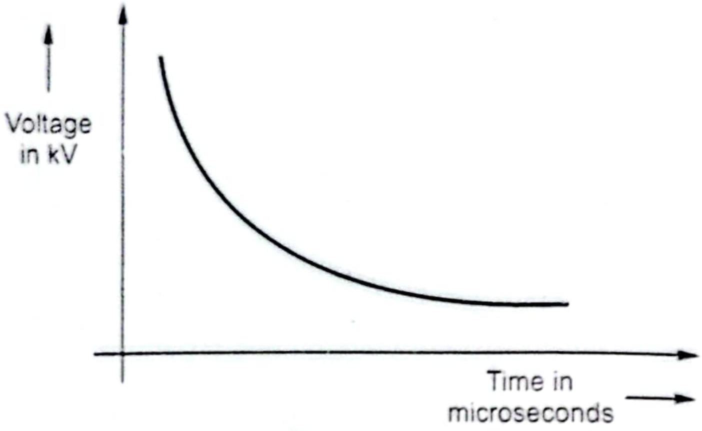


Fig. A.4.2

Under normal operating conditions the gap is non-conducting. When the high voltage surge occurs on the line, there is spark over in the gap and current in surge is diverted to the earth. Thus excessive charge on the line is passed to the earth through this arrester. The volt-time characteristics for a rod gap is shown in the Fig. A.4.2.

With the given gap and the wave shape of the voltage, the time required for the breakdown varies inversely with the voltage. The time for flash over for positive polarity is less than that for negative polarity. Upto certain extent the flash over voltage depends on the length of grounded rod. There is considerable difference between positive and negative flash over voltages for low values of this length. If the length is about 1.5 to 2 times the gap spacing then it is sufficient to reduce this difference applicably. The gap setting is in such a way that its breakdown voltage should be more than 30 % below the voltage level of the equipment to be protected that it can withstand.

A.4.1 Limitations

Following are limitations of rod gap arrester.

1. Precise protection is not achieved and is not reliable so it can not be used as main protection against surge in high voltage systems. But as it is cheap it can be a good choice for second line of defence.
2. It gives protection against waves with comparatively small sloping front. Also the breakdown voltage varies with polarity, steepness and waveshape. The performance is affected by polarity of surge.
3. The rods may get damaged due to excess heat produced by arc. This is an important consideration in high voltage systems.

4. The performance is affected adversely due to climatic conditions such as humidity, temperature pressure.
5. The power frequency follow current is not interrupted by this type of arrester and it continues, to flow even after the high voltage surge is over. This creates a line to ground (or earth fault) fault which is to be interrupted by circuit breaker. Thus the operation of rod gap results in interruption of supply and breakers must operate to de-energize the circuit to clear the flash over. The arc set up across the gap due to surge current ionizes the surrounding air which affects the insulation strength of the gap. Also sufficient time must be provided for deionization of arc path before the reclosure of circuit breaker for restoring supply. Hence it is generally used as back up protection.

There are some improvements in rod gap such as fused gap and control gap which are also used in practice sometimes. The fused gap is simply a rod gap along with a fuse in series with it to cut the power follow current. But it requires replacement and maintenance of fuse. Also for its effective operation it requires proper co-ordination between blowing of fuse and adjacent relay timing.

The control gap consists of a double gap arrangement to get sphere gap characteristics. Compared to rod gap its volt-time characteristics are better. It can be used with or without fuses and used as a back up or secondary protection.

Review Question

1. *Describe the construction, principle of operation and application of rod gap arrester.*

A.5 Multigap Arrester

It consists of a series of metallic cylinders made up of alloy of zinc generally insulated from one another and separated by small air gaps as shown in the Fig. A.5.1.

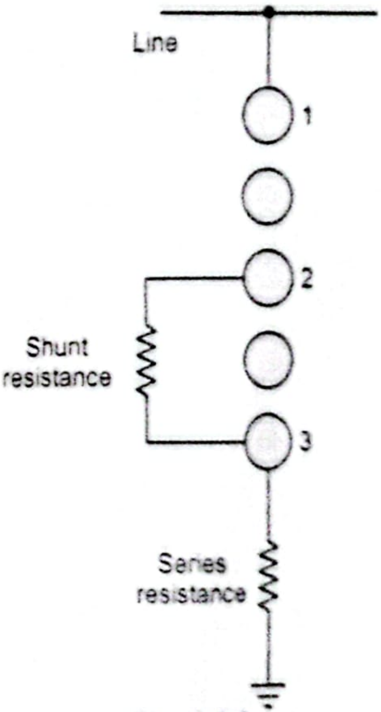


Fig. A.5.1

Cylinder 1 is connected in series with the line while cylinder 3 is connected to earth through a series resistance. The series resistance limits the arc. The protection against travelling waves is reduced due to series resistance. To overcome this difficulty shunt resistance is included in some of the gaps.

Under normal operating conditions, cylinder 2 is at earth potential and it is not possible to breakdown the series gaps by normal voltage.

When overvoltage occurs, there is breakdown of the gap between 1 and 2. The large current will pass through the gaps instead of choosing an alternate path through shunt resistance and will divert to the earth.

After the surge is over, there is no arc in between 2 and 3, the power follow current is limited by shunt and series resistances as they are now in series. The current is not enough to maintain arc in the gap between 1 and 2 and normal conditions are restored. These arresters are used for system voltages upto 33 kV.

Review Question

1. *Describe the construction and principle of operation of multistage arrester.*

A.6 Expulsion Type Arrester

This type of arrester is also known as protector tube and used wherein the system voltages are upto 33 kV. The constructional features of such arrester is shown in the Fig. A.6.1.

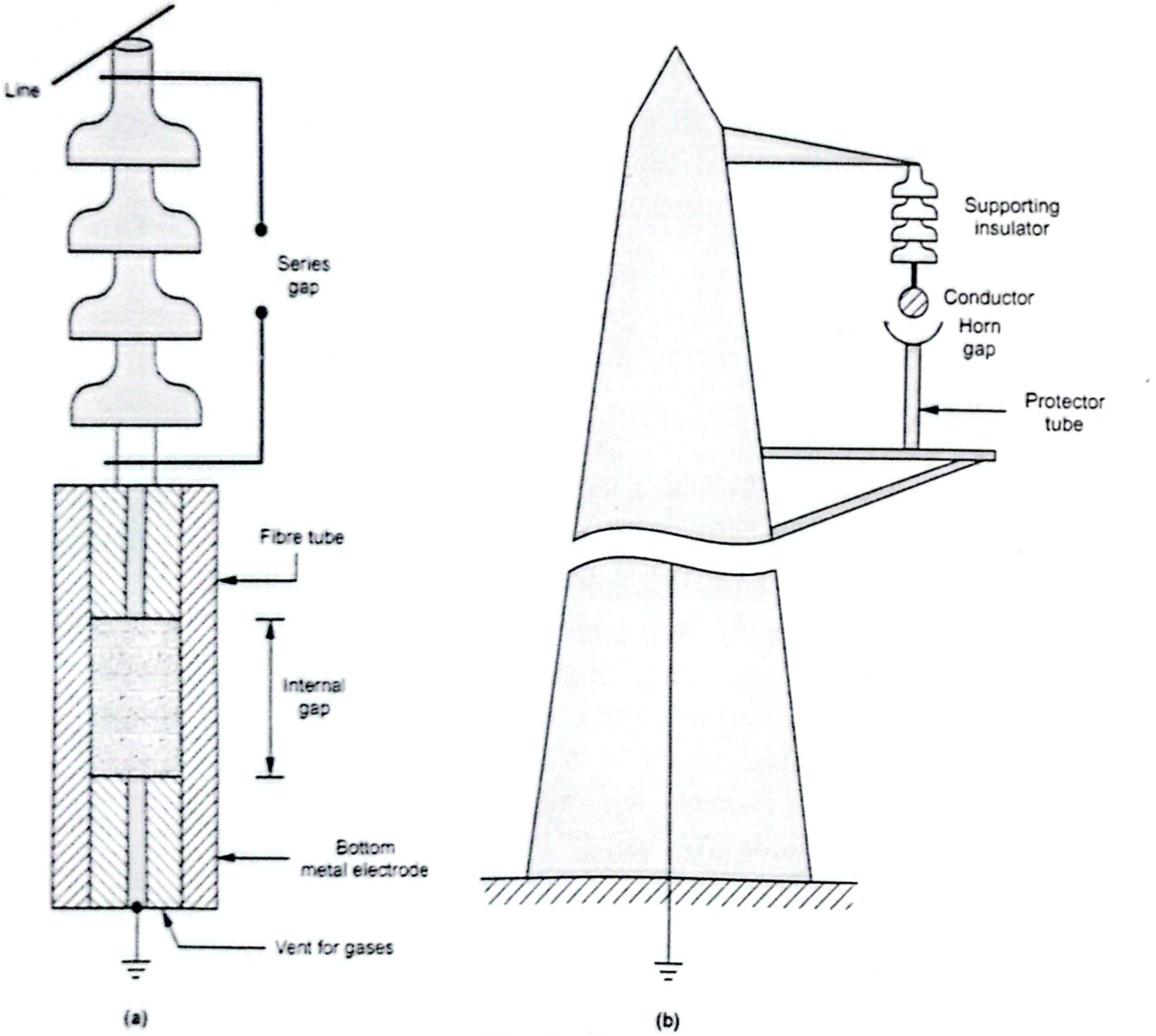

Line
Series gap
Fibre tube
Internal gap
Bottom metal electrode
Vent for gases
(a)
Supporting insulator
Conductor
Horn gap
Protector tube
(b)

Fig. A.6.1

This is an improvement in the rod gap in the following aspects.

i) It consists of a series gap which is external to the tube which can withstand normal system voltage hence there is no possibility of corona or leakage current across the tube.

ii) It has a tube having fibre lining from inside which is highly gas evolving material.

iii) The internal gap inside the tube.

iv) It has an open vent at the bottom for releasing the gases.

It consists of a series gap in series with internal gap inside a fibre tube. This gap in the fibre tube is made up of two electrodes. The upper electrode is connected to the series gap while the lower electrode is connected to the earth. One such arrester is placed under each line conductor. It is required that the breakdown voltage of the tube should be less than that of the insulation for which it is used.

Whenever over voltage occurs on the line, there is breakdown in the series gap and arc is formed between the electrodes in the tube. Thus providing a low impedance path for lightning current to earth.

The heat produced by the arc vapourizes some of the organic material in the tube. The resulting natural gas builds up high pressure in short time and expelled out through the bottom vent after producing lot of turbulance in the tube. After the gas leaving from the tube violently, it carries ionized air around the arc.

Due to this strong de-ionizing effect, the arc is extinguished without restriking making current zero. The arc extinction time is about one or two half cycles which is very short interval for protective relays to act. Hence circuit breakers remain closed and line is kept in operation. After the expelling of gases and arc suppression, the tube is ready for new operation. The power follow current is safely interrupted by this type of arrester.

With each operation of the tube the diameter of the fibre tube is increased as some part of fibre lining is vapourized every time which lowers insulation characteristics of tube. The volt-time characteristics are better than rod gap type and are shown in the Fig. A.6.2.

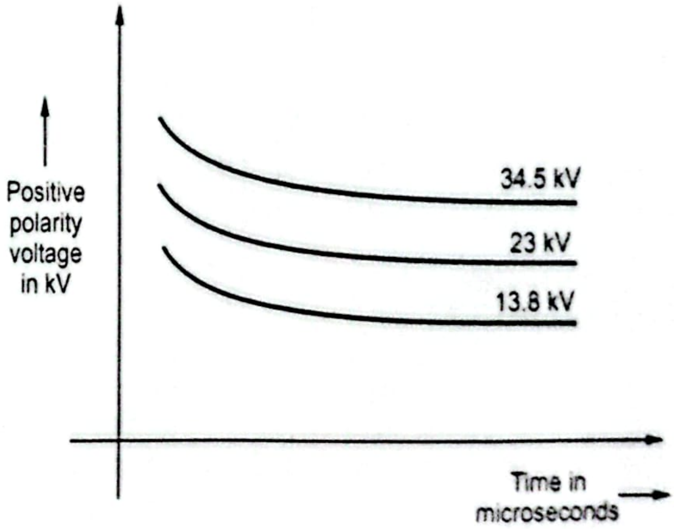


Fig. A.6.2

Excessive current flowing through the tube may cause its bursting while a small current will be insufficient for producing necessary pressure to extinguish the arc. Also as the gas producing material is utilized each time when arrester operates, there is limitation of number of operations which can be safely carried by this arrester. Since there is gaseous discharge, it is not suitable for mounting near other equipments.

A.6.1 Advantages

1) They are cheaper and can be installed easily.

2) They are capable of interrupting power follow current immediately after the surge is over.

A.6.2 Disadvantages

1) The volt-amp characteristics for this arrester is poor and hence can not be used for protection of expensive station equipments.

2) It cannot be mounted in an enclosed equipment because of discharge of gas during its operation.

3) It can perform limited number of operations as some of the fibre is used in every operation to produce gas for extinguishing the arc.

These types of lightning arresters are used on transmission towers near to the stations in certain cases to make the station lightning arrester free from its duty to certain extent by reducing the magnitude of surges coming on the line.

They are also used for protection against surges for transformers in rural areas as they are cheap than valve type arresters. These arresters are also employed in some special cases such as transmission towers with more height wherein there are more chances of lightening strokes.

Expulsion type arresters are either transmission type used for transmission line insulators or distribution type for the protection of distribution transformer and similar apparatus on distribution networks.

Review Question

1. *Describe the construction, principle of operation and application of expulsion gap arrester.*

A.7 Thyrite Type (Valve Type) Arrester

It is an expensive surge diverter also known as non-linear surge diverter. The details of this arrester are shown in the Fig. A.7.1.

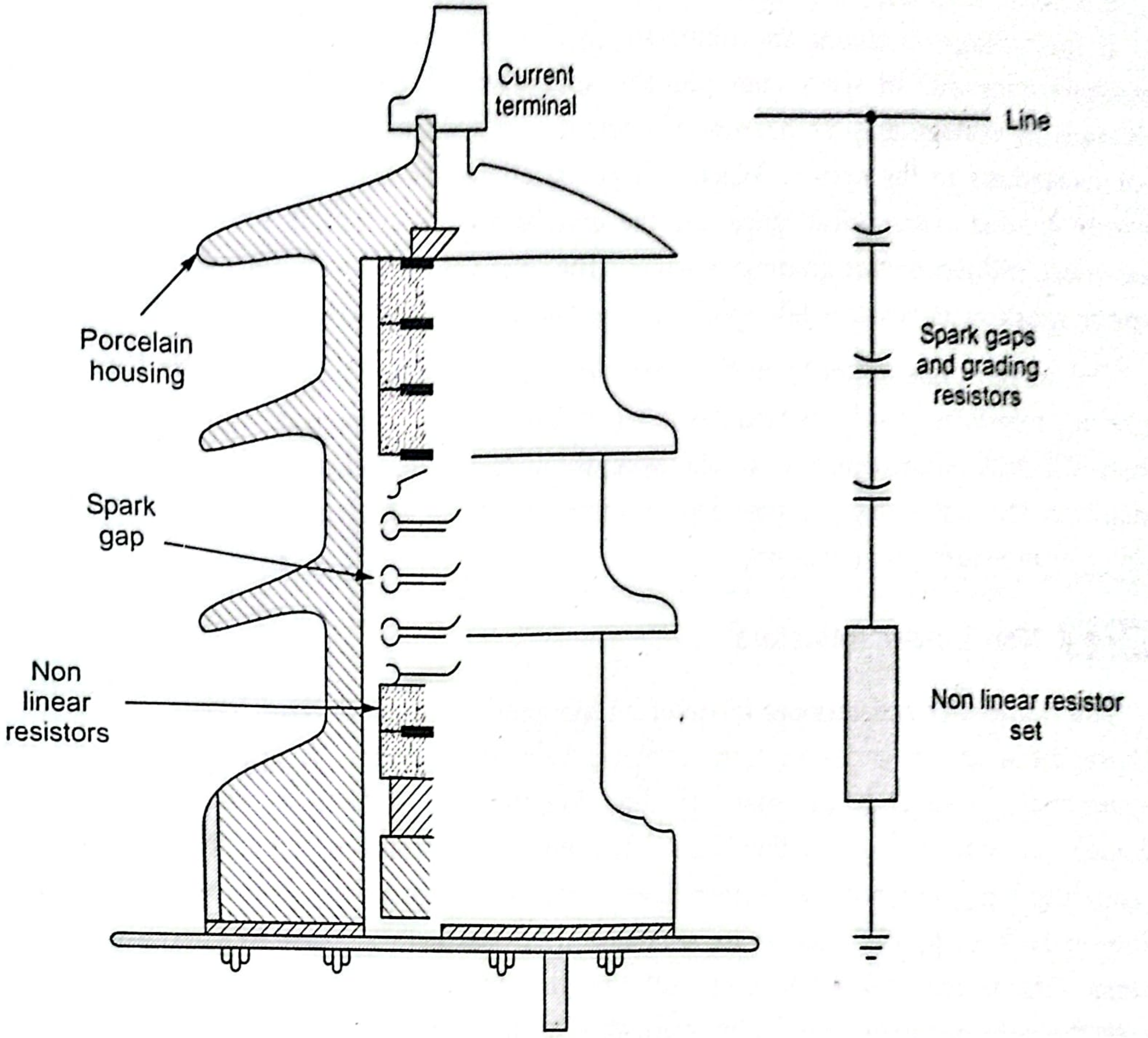

Current terminal
Porcelain housing
Spark gap
Non linear resistors
Line
Spark gaps and grading resistors
Non linear resistor set
(a)
(b)

Fig. A.7.1

As shown in the figure, there are two assemblies viz.

i) Series spark gaps

ii) Non linear resistor discs made up of material such as thyrite or matrosil in series.

The non linear elements are in series with the gap. Both these assemblies are contained in tight porcelain container for reliable protection against moisture, humidity and condensation.

A.7.1 Series Spark Gap Assembly

It consists of number of series gaps consisting of two electrodes with fixed gap spacing. The voltage distribution across the spark gaps is made linear with the help of additional resistors called grading resistors of high value across the gap. The normal system voltage is easily withstood by spacing of series gaps. With high voltage, there will be breakdown of spark gap to divert the surge current to earth through non-linear resistors.

If the voltage variations are comparatively slow, then because of influence of grading resistors over that of spark gaps prevents sparkovers that may be caused due to slow changes in voltage may be because of internal over voltages during coupling operations not hazardous to the system. When voltage variations are fast, then the potential is not evenly graded across series gaps and the unbalancing capacitances between spark gaps has more influence over grading resistors. The over voltages are mainly concentrated on upper spark gaps which while sparking over cause complete arrester to spark over too.

The interrupting capacity of the spark gaps unit can be increased with the help of grading resistors. Under normal working conditions, the leakage current is always less than 0.1 mA approximately which flow through the resistors. This is sufficient to maintain the enclosures at specified temperature above ambient so as to prevent the effect of moisture into enclosure.

A.7.2 Non Linear Resistors

The non-linear resistors are made of an inorganic compound viz. Thyrite or Metrosil. These discs are in series to form a block. With the increase in applied voltage and current, the resistance decreases quickly. The residual voltage is hence maintained though current is high within limit. The non-linear resistors have the property of providing high resistance to current flow of normal system voltage but low resistance to flow of high surge currents i.e. its resistance decreases with increase in current and vice versa. Hence the power follow current after the surge is over can be easily interrupted with the help of resistor blocks by spark gaps at first current zero.

A.7.3 Working

Under normal operating conditions, the system voltage is not enough to cause breakdown of air gap assembly. Under the condition of over voltage, there is breakdown of series spark gaps and the surge current quickly reaches to ground through non linear resistors. The non-linear resistors will offer very small resistance to the flow of surge current whose magnitude is large. Thus the surge is prevented from sending back over the line. After the surge is over, the resistor blocks offers high resistance to the flow of power follow current and the current is interrupted. After approaching towards the equipment to be protected, the surge takes around 0.25 μsec to reach to the arrester and the whole operation of arrester takes place in a very short interval of time in about 20 to 30 μsec. The arc is extinguished at first current zero by cooling and lengthening of arc and also the voltage and current are almost in phase.

The volt-ampere characteristics of valve type lightning arrester is shown in the Fig. A.7.2.

The closed curve represents the dynamic characteristics corresponding to application of voltage surge while the dotted line showing static characteristics. The horizontal tangent drawn to the dynamic characteristics gives the voltage known as residual voltage and is the peak voltage during discharge of surge current.

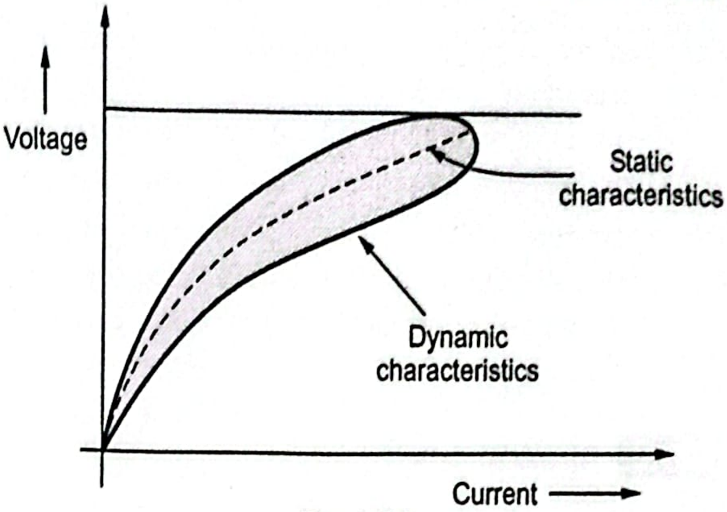


Fig. A.7.2

Depending upon the type of the arrester i.e. either line type or station type discharge voltage varies from 3 kV to 6 kV. This voltage is also affected by magnitude and waveshape of discharge current.

The impulse ratio of unity is obtained for this arrester according to design of spark gaps. Hence high values of surge currents can not be interrupted. The impulse breakdown strength is smaller than residual voltage which decides the protection level for insulation co-ordination.

The volt-current relationship for one type of thyrite disc (non-linear resistor) is given by,

$$\boxed{V = K I^{\alpha}}$$

Resistance of the arrester $= \frac{V}{I} = \frac{K I^{\alpha}}{I} = \frac{K}{I^{1-\alpha}} = \frac{K}{I^{\beta}} = K I^{-\beta}$

Typical values of K and β are 4650 and 0.72.

With N number of thyrite discs,

Resistance, $$\boxed{R = \frac{N K}{I^{\beta}} = N K I^{-\beta}}$$

∴ $$R I^{\beta} = NK = \text{Constant}$$

A.7.4 Advantages

i) The operation of this arrester is very fast within a fraction of second.

ii) They are suitable for effective protection of transformers and cables against surges.

A.7.5 Disadvantages

i) Very steep wave front type of surges are not being protected by these arresters. Fortunately the lightning surges on the transmission system are attenuated as they travel over the line towards the substations and they are within the reach of protection circuits in the substations. But proper care should be taken to prevent surges of severe intensity and efficient form of shielding should be used.

ii) The performance of this type of arrester may be affected if there is entry of moisture in the enclosure. This problem can be solved by sealing the container hermetically or enclosures are filled by inert gas and contain some form of de-humidifier or allowing the leakage current to pass to maintain the temperature within limits.

A.7.6 Applications

The valve type arrester is classified in following types.

i) Station type :

These arresters are efficient and expensive which are used for protection of important equipments with rating from 2.2 kV to 400 kV and higher. It has highest capability for dissipation of energy.

ii) Line type :

The term "Line" is misleading as these arresters are not used for protection of lines. Unlike station type, these are also used for protection of plants and substations which are comparatively less important and economy is to be achieved. They are used upto 66 kV except in some cases beyond it. They are smaller in cross section, weight and cost than station type. They provide protection against higher surge voltages than station type but have less surge current capacity. Typical ratings of these arresters are upto 5 kA to use in large transformers and intermediate substations.

iii) Arrester for protecting rotating machines :

These are specially used for protection of generators and motors with voltage range from 2.2 kV to 22 kV.

iv) Distribution type arrester :

These are generally used for protection of pole mounted distribution substations and are available in the voltage range from 2.2 kV to 15 kV.

v) Secondary arresters :

These are used for protection of low voltage apparatus with the range of 120 V to 750 V.

Review Question

1. *Describe the construction, principle of operation and application of valve type arrester.*

A.8 Metal Oxide (ZnO) Type Arrester

This is a new type of lightning arrester developed and used. It consists of non-linear resistor block and main element of the arrester is metal oxide or normally zinc oxide (ZnO) which is economical compared to thyrite arresters. There are no series gap and its degree of non-linearity is more than that of thyrite arrester.

The ZnO type of arrester provides better surge protection with more stable protection characteristics and has simple construction similar to valve type but the valve element is a dense ceramic body made up of ZnO and other metallic oxides.

The Fig. A.8.1 shows cross-sectional view of ZnO surge arrester.

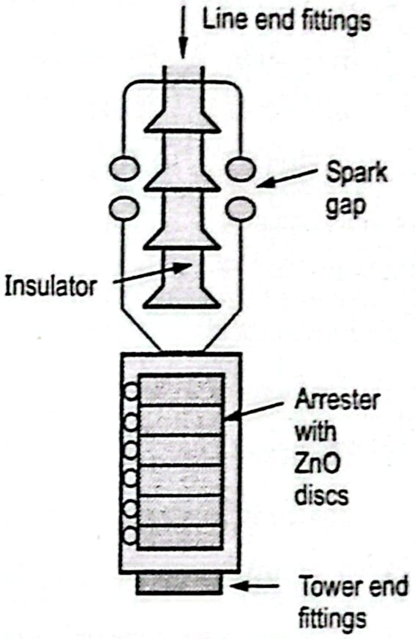


Fig. A.8.1 ZnO type arrester

The ZnO discs are arranged in a cylindrical stack. The stack is put inside a porcelain housing. The stacks are supported using spring loaded cups at top and bottom. The zinc oxide (ZnO) has highly non-uniform current-voltage characteristics for over voltage suppression.

After electrodes are fitted at either end, the remaining space is filled with fibre reinforced composite material. The performance of ZnO blocks for fast rising over voltages is very effective due to its large energy absorbing capacity.

The nonlinear characteristic of ZnO is given by,

$$I = kV^{\alpha}$$

Where k depends on dimensions of the block and α is more than 30 for ZnO.

The V-I characteristics of ZnO type arrester is shown in the Fig. A.8.2.

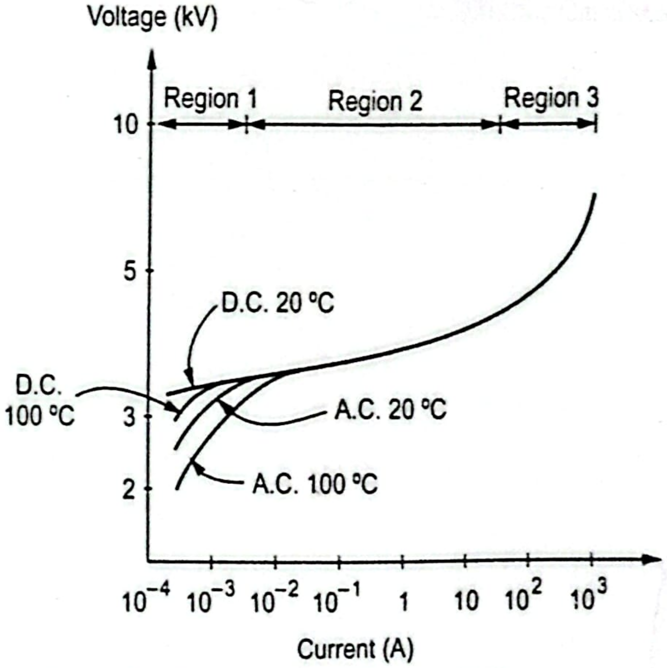


Fig. A.8.2 V-I characteristics of ZnO arrester

1. In region 1, the current is less than 1 mA and it is capacitive in nature.

2. In region 2, the current varies from 1 mA to 1000 A and is resistive in nature.
3. In region 3, the current is very large more than 10^3 A and characteristics approaches to linear relationship with voltage V.

When the over voltage occurs, then current rises according to the nonlinear characteristics without any delay. This puts arrester into conducting state and surge is conducted to the earth.

The advantages of metal oxide arrester are,

1. The series gaps are not required, which eliminates number of parts.
2. The size is very small.
3. The construction is very simple and it is totally solid state protective device.
4. Highly reliable and cost effective.
5. The response is very quick.
6. Its durability is high for multiple operating duty cycle.
7. Negligible follow up current after the large operation takes place.
8. Time delay is very small while responding to over voltages.
9. It has very high energy discharge capability.

Review Questions

1. *Draw metal oxide arrester and explain its construction and working. List its advantages over other arresters.*
2. *Discuss the different types of lightning arresters with neat diagrams.*

AU : May-19, Marks 15

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